Beam-Beam Effects in High-Luminosity LHC Upgrade

A.Valishev (Fermilab/US LARP), S.Fartoukh (CERN), D.Shatilov (BINP)

Acknowledgments: HL-LHC WP2 colleagues

Fermilab APT Seminar
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Outline

This talk concentrates on effects of beam-beam interactions during collisions on beam dynamics, leaving all other topics aside

- LHC design goals
- 2012 operation
- LH-LHC upgrade, its goals and challenges
- Beam-beam modeling
- Baseline HL-LHC scheme
- Crab Kissing scheme
  - Flat optics and Wire compensator
  - Crab Crossing, Crab Kissing
  - Flat bunches

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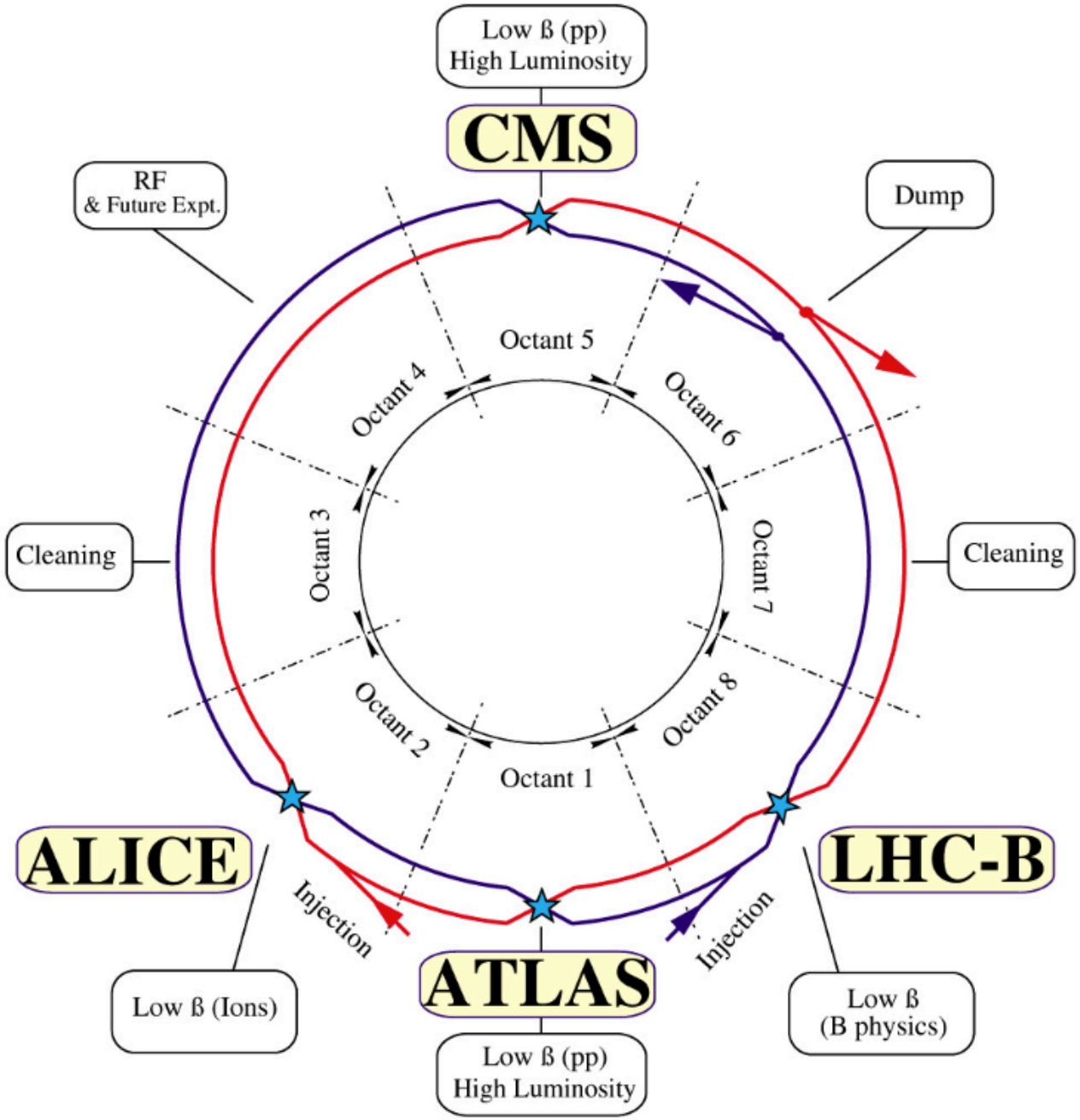
Low ß (pp)
High Luminosity
CMS
RF
& Future Expt.
Dump
Octant 5
Octant 4
Octant 6
Octant 3
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Cleaning
Cleaning
Octant 2
Octant 8
Octant 1
ALICE
LHC-B
Injection
Injection
ATLAS
Low ß (Ions)
Low ß
(B physics)
Low ß (pp)
High Luminosity

LHC design parameters

	LHC nominal
Beam energy	7 TeV
Number of bunches	2808 (25 ns separation)
protons / bunch [10^{11}]	1.15 (0.58A)
Energy in one beam [MJ]	360
$\gamma\varepsilon_{x,y}$ [μm], rms	3.75
σ_z [cm], $\sigma_{\delta p/p}$ [10^{-3}]	7.5, 0.1
β^* [m] at IP1-5, 8	0.55, 10
Beam-beam tune shift (total from 3IP)	0.01
X-angle [μrad], separation	285, 9.3 σ
Geometrical Luminosity loss factor	0.83
Peak luminosity [10^{34}]	1.0
Pile up	25

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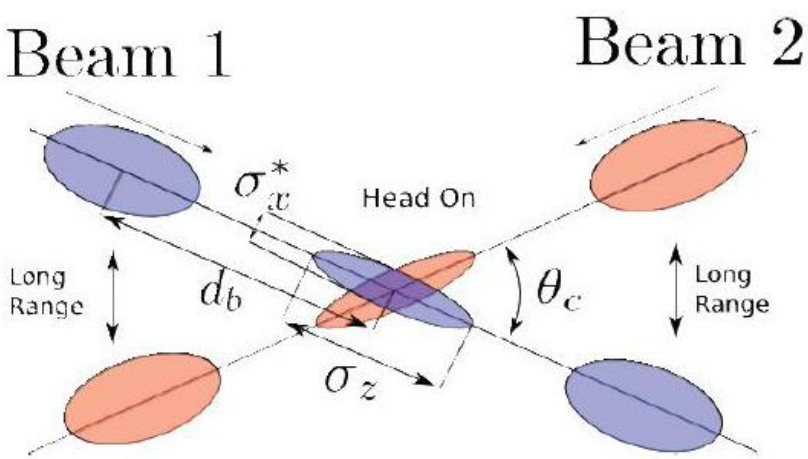
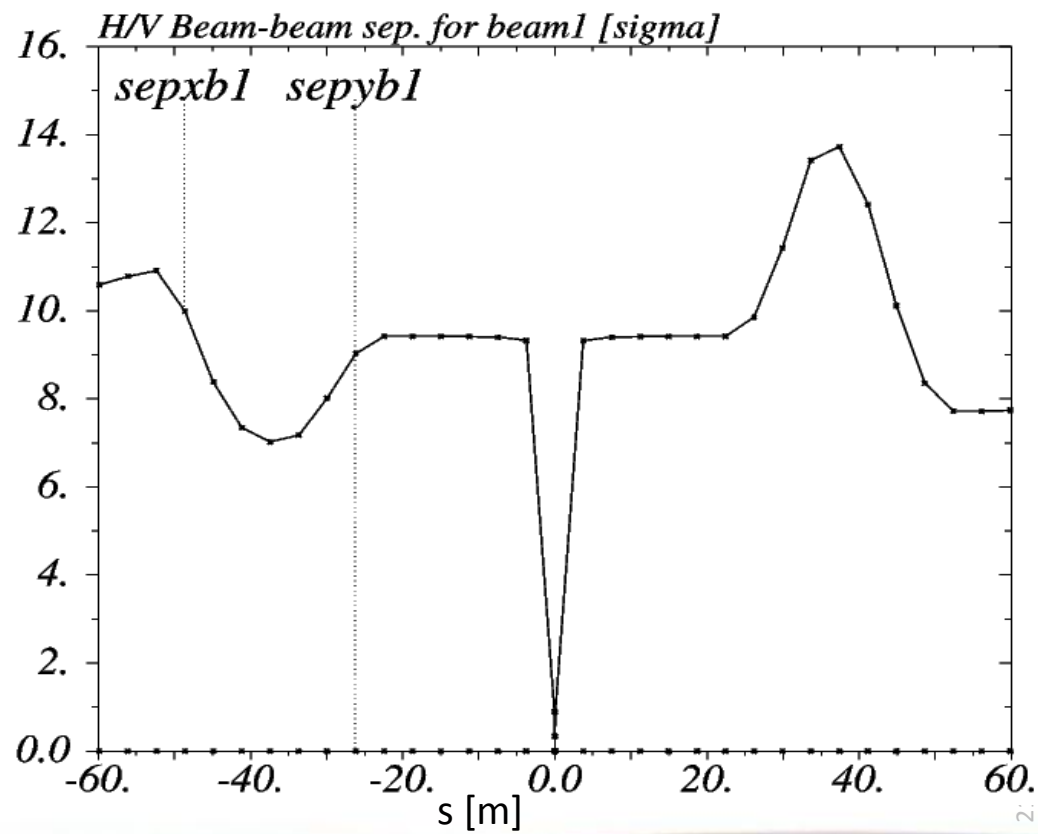
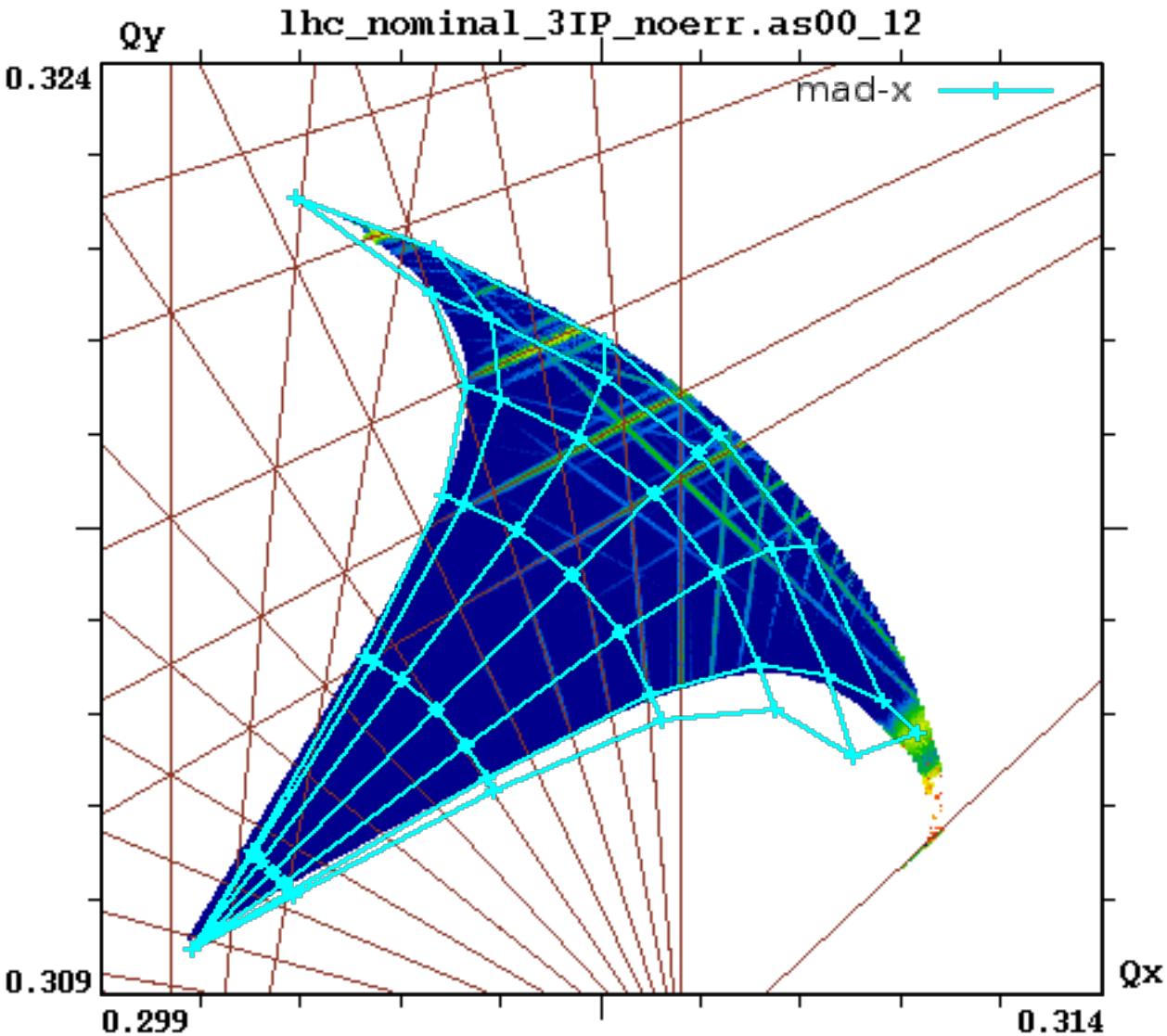
Head-on and long-range collisions

- 3 head-on IPs
  - IP1,5 low-beta – β*=55cm
  - Low luminosity IP8 β*=10 m
- ~100 long-range IPs
  - IP5,8 – horizontal sep.
  - IP1 – vertical separation





Beam-beam footprint



LHC operation in 2012

	LHC nominal	2012
Beam energy [TeV]	7	4
Number of bunches	2808 (25 ns sep.)	1368 (50 ns sep.)
protons / bunch [10^{11}]	1.15 (0.58A)	1.6-1.7 (0.4A)
Energy in one beam [MJ]	360	140
$\gamma\varepsilon_{x,y}$ [μm], rms	3.75	2.5
σ_z [cm], $\sigma_{\delta p/p}$ [10^{-3}]	7.5, 0.1	10, 0.1
β^* [m] at IP1-5, 8	0.55, 10	0.6, 10
Beam-beam tune shift (total from 3IP)	0.01	0.022
X-angle [μrad], separation	285, 9.3 σ	290, 9 σ
Geometrical Luminosity loss factor	0.83	0.93
Peak luminosity [10^{34}]	1.0	0.77
Pile up	25	40

ξ=0.022 but half the number of long-range IPs, ~45

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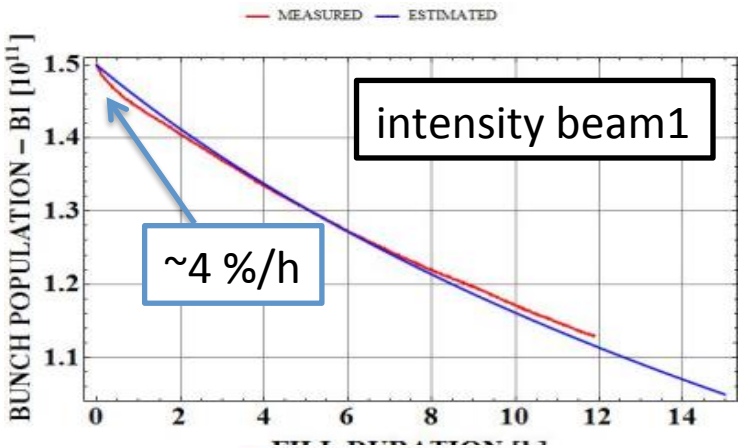
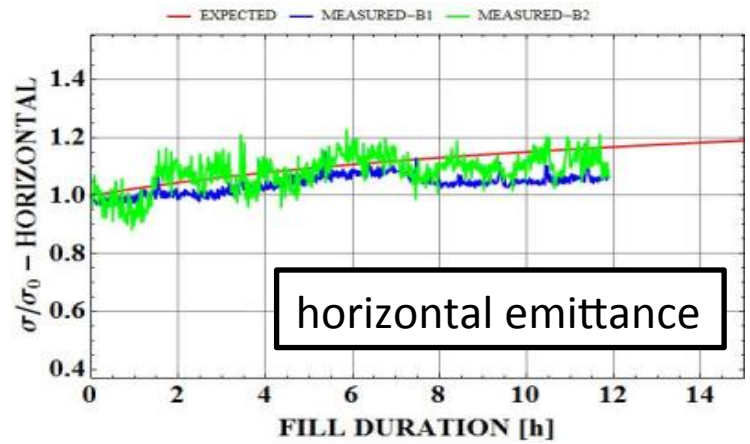
LHC operation in 2012

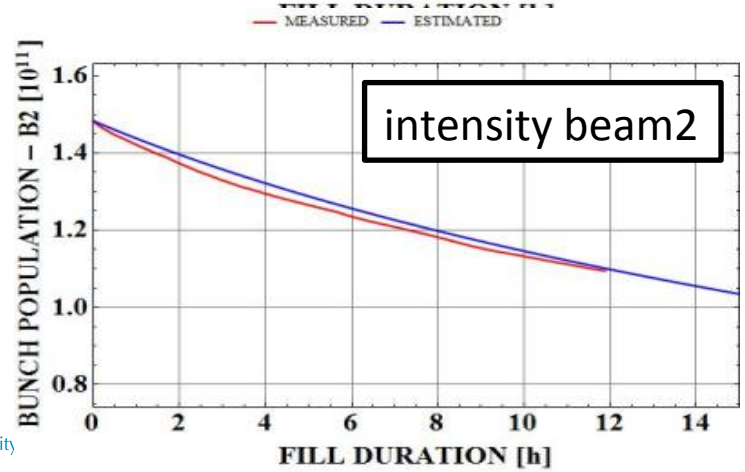
G.Arduini

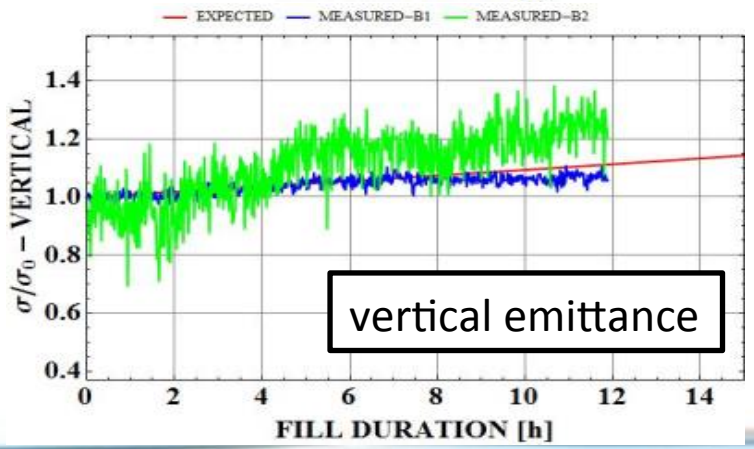
Luminosity evolution for fill 2728 compared to model including

- Particle losses due to luminosity and unknown source τ=200 h
- Emittance growth due to IBS, SR damping and unknown growth with τ=40 h









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LHC operation in 2012

G.Arduini

Luminosity evolution for fill 2728 compared to model including

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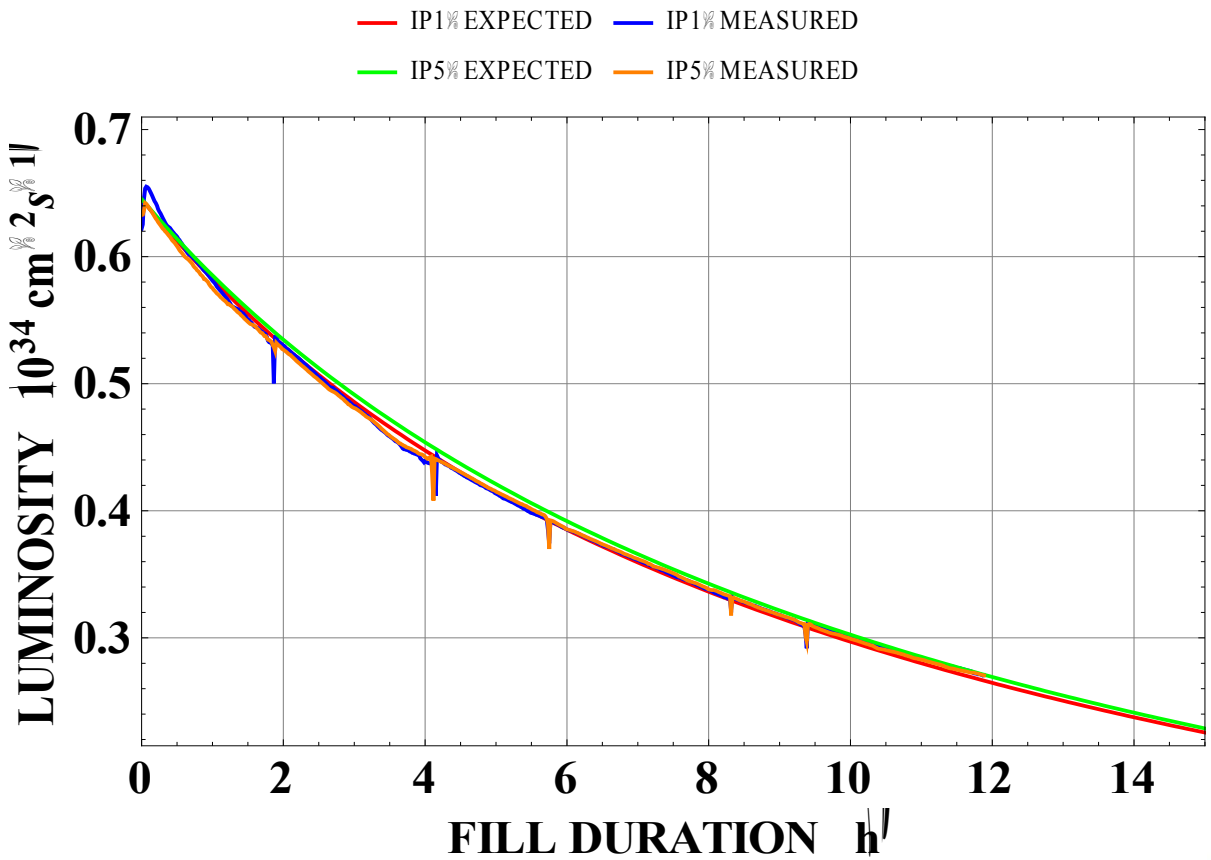
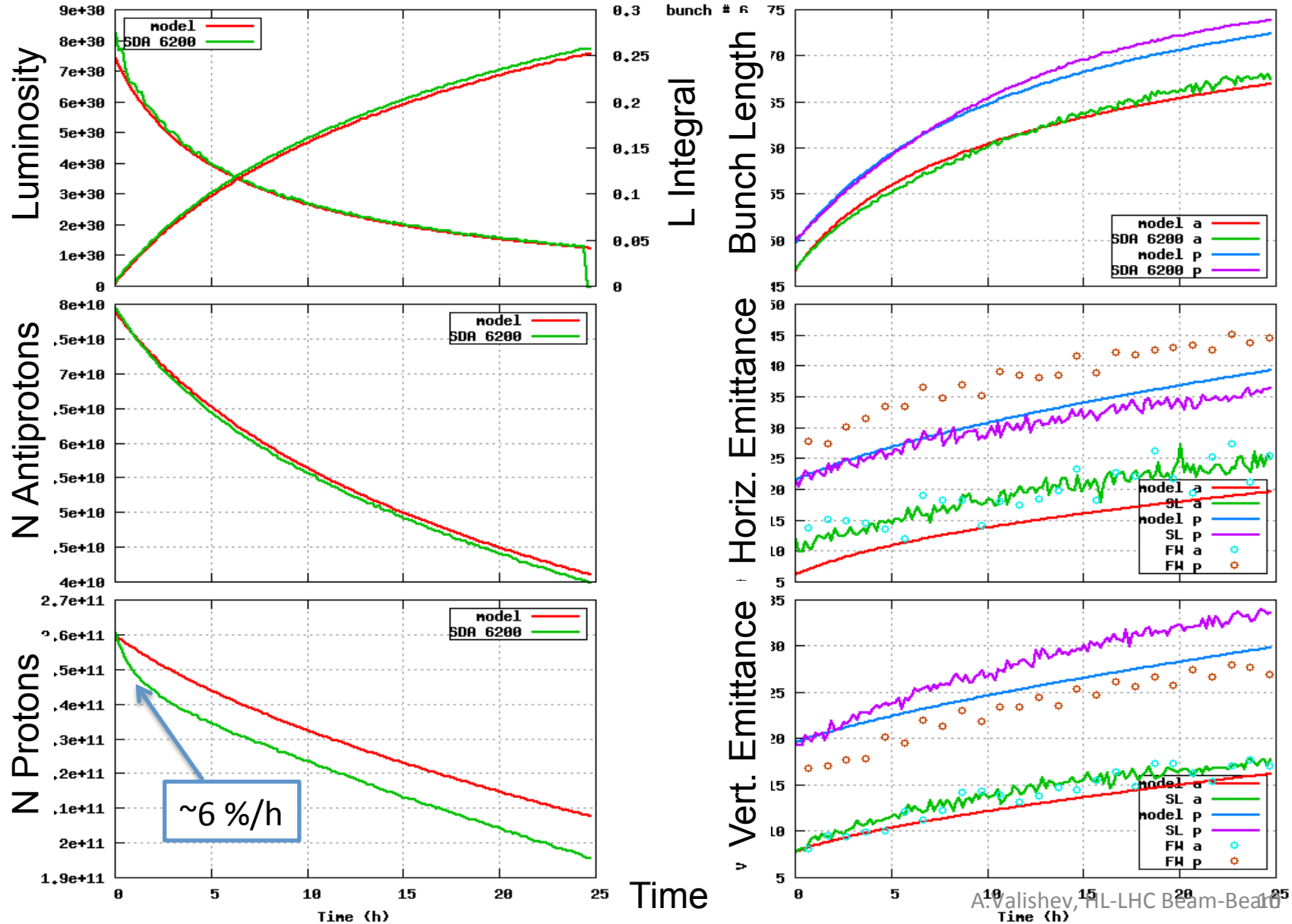
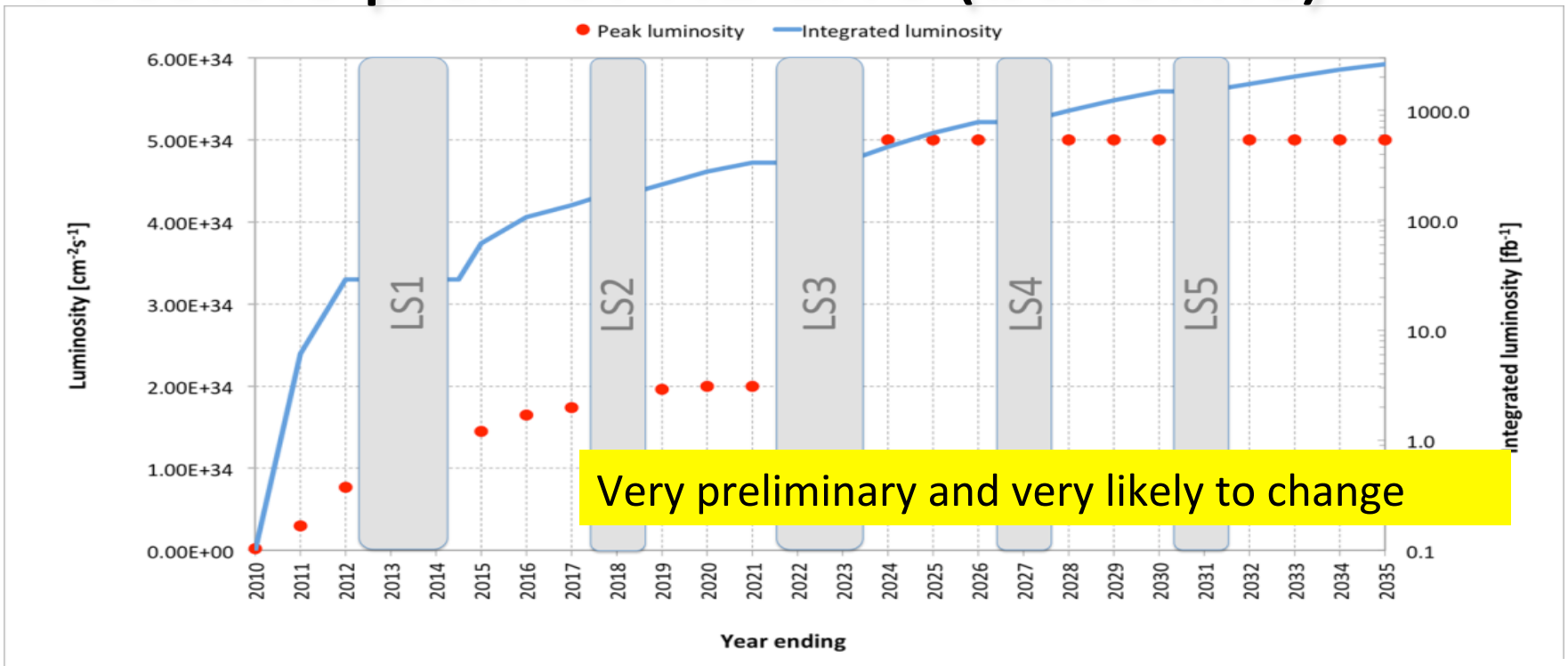


Tevatron store 6200, L_0=2.95x10^{32}



Possible plan of HL-LHC (baseline)



Levelling at 5 10^{34} cm^{-2} s^{-1}: 140 events/crossing in average, at 25 ns; several scenarios under study to limit to 1.0 → 1.3 event/mm

Total integrated luminosity of 3000 fb^{-1} for p-p by 2035, with LSs taken into account and 1 month for ion physics per year.

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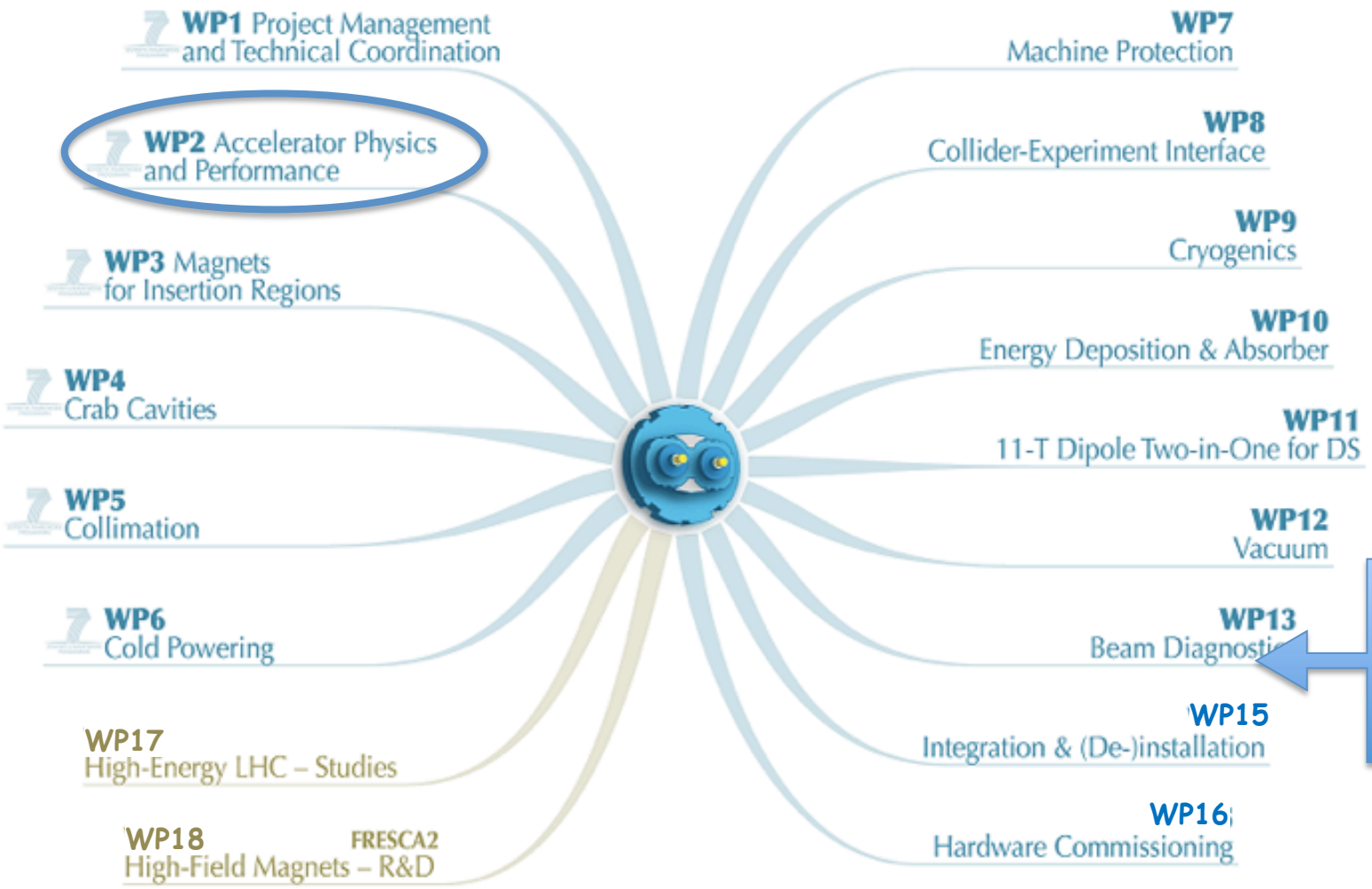
The High Luminosity LHC
Frédérick Bordry
ECFA High Luminosity LHC Experiments Workshop – 1st October 2013

European HiLumi LHC design study

Work Packages



WP14 Beam Tr. Lines and Kickers

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HL-LHC baseline parameters

	LHC nominal	HL-LHC 25 ns
# Bunches	2808	2808
p/bunch [10^{11}]	1.15 (0.58A)	**2.2 (1.11 A)**
Energy in one beam [MJ]	360	**690**
$\gamma\varepsilon_{x,y}$ [μm]	3.75	**2.5**
σ_z [cm], $\sigma_{\delta p/p}$ [10^{-3}]	7.5, 0.1	7.5, 0.1
β^* [cm]	55	**15 (→ 10)**
X-angle [μrad], separation	300, (10.0 σ)	**590 (→ 720), (12.5 σ)**
Geometrical luminosity loss factor	0.83	0.31
Peak lumi [10^{34}] (with full Piwinsky angle)	1.0	7.4
Virtual lumi [10^{34}] (w/o Piwinsky angle)	1.2	21.9
$T_{leveling}$ [h] @ 5E34	n/a	**9.0**
#Pile up @5E34	25	**140**

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HL-LHC conceptual baseline

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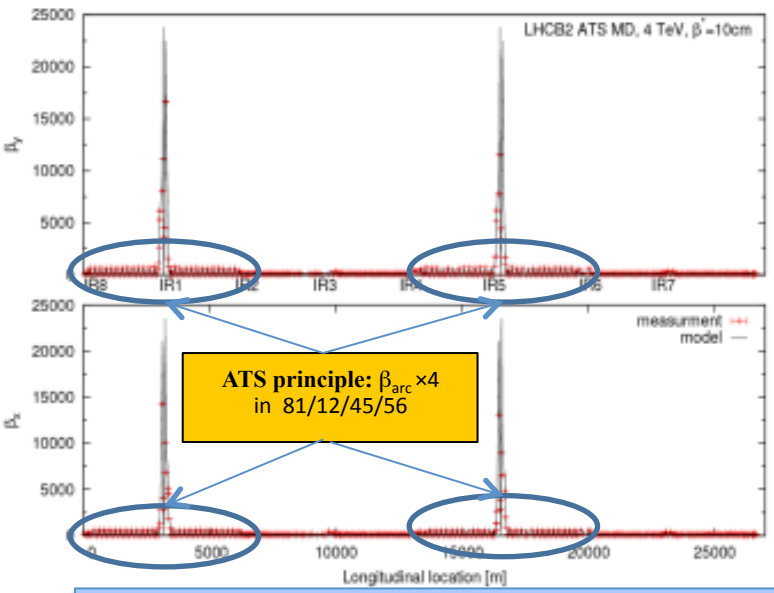
- **Optics and crab-cavities (... short description)**

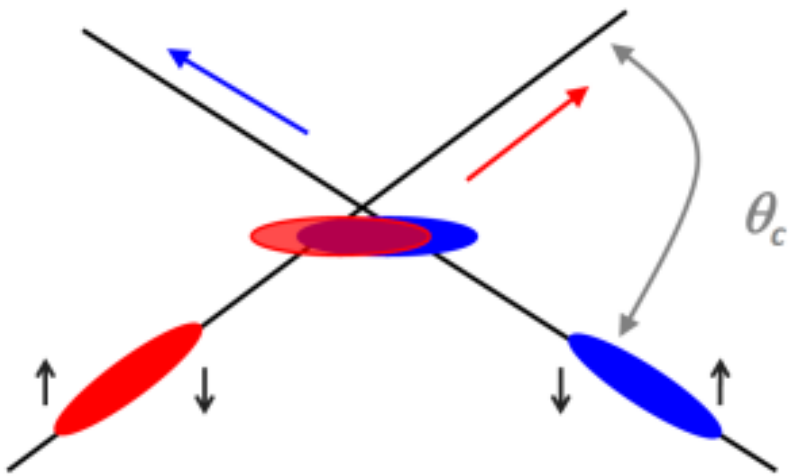
→ **``Round'' ATS collision optics with aggressive β^*** of 15 cm (→ 10 cm) in H and V

→ **``Large'' X-angle** of 590 μrad (→ 720 μrad) ``compensated'' by **crab-cavities**

→ **Lumi leveling @ 5E34 with β^* @ max CC voltage of 12.5 MV** (→ 15 MV)



The 10 cm β^* ATS MD (CERN-ATS-NOTE 2013-004 MD)



F. Zimmermann, R. Calaga et al.

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HL-LHC running scenario

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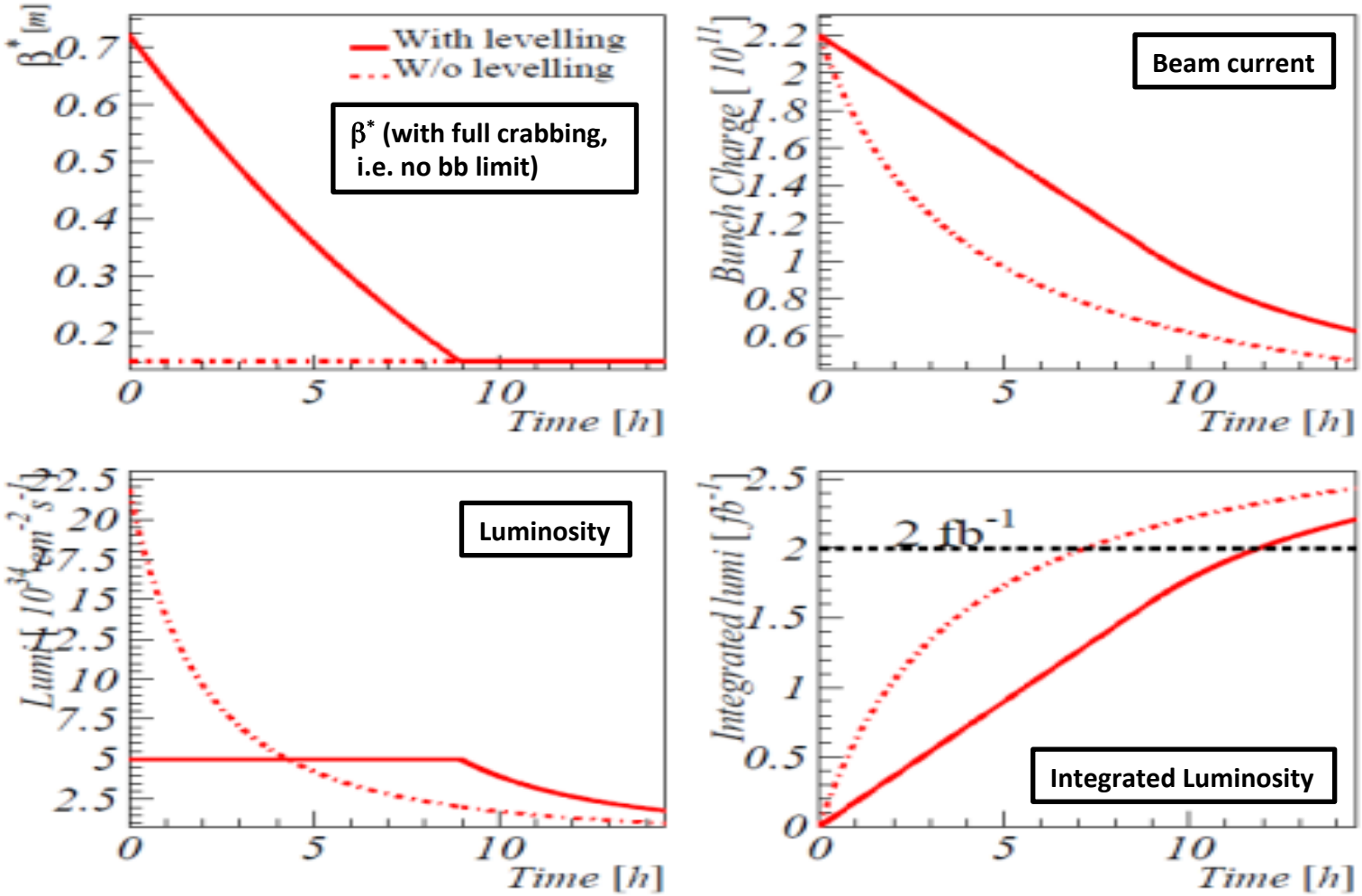

HL-LHC conceptual baseline

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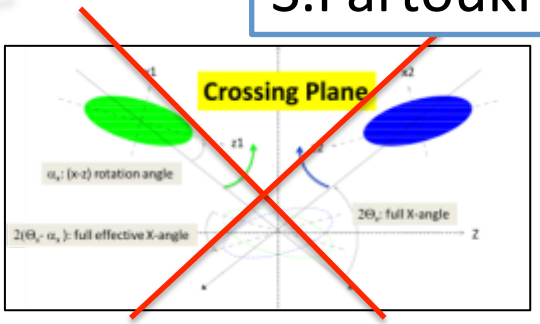
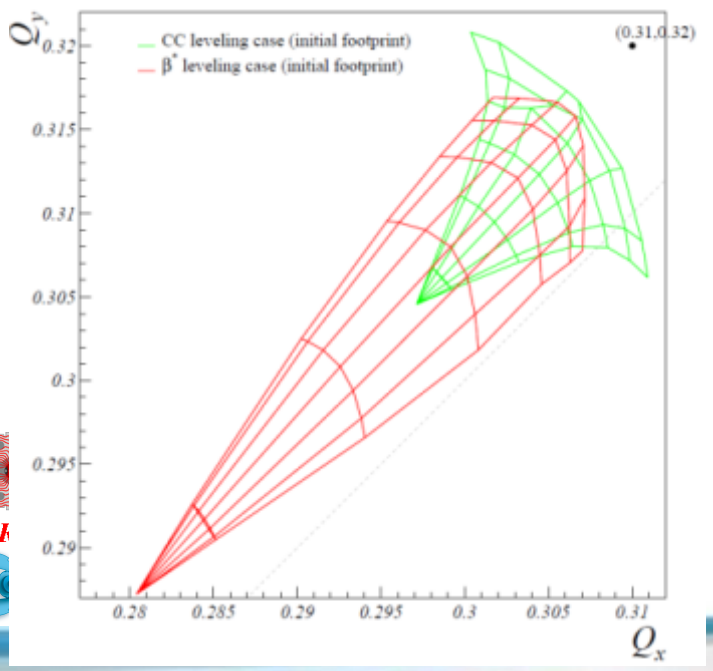


- **Leveling (1st big challenge)**

→ **Using crab-cavities** reduces the bb tune shift but is prohibited by a **too small luminous region**

→ **Using β*** instead is **presently** the preferred option (BB2013) but leading **to ΔQ_{bb}=0.033** for 3 IRs (including LHCb). Seems to work in simulation, but might be difficult to "handle" in practice (with noise, magnet imperfections, ...)



Parameters	Leveling with CC	Leveling with β*
# bunches	2760	
bunch charge [10^{11}]	2.2	
emittance [μm]	2.5	
r.m.s. bunch length [cm]	7.5	
full X-angle [μrad]	590	
initial β* [cm]	15	68
c.-c. initial voltage [MV]	- 6.6	12.5
initial Piwinsky angle	4.76	0
initial lumi loss factor	0.21	1.0
levelled lumi [10^{34}cm^{-2}s^{-1}]	5.0	
initial luminous region [cm]	**1.1 (~5-6 evt/mm)**	**4.4 (~1.3 evt/mm)**
initial bb tune shift for 3 IRs (IR1, IR5 & IR8)	**0.016** (0.011+2×0.0025)	**0.033** (3×0.011)

HL-LHC conceptual baseline

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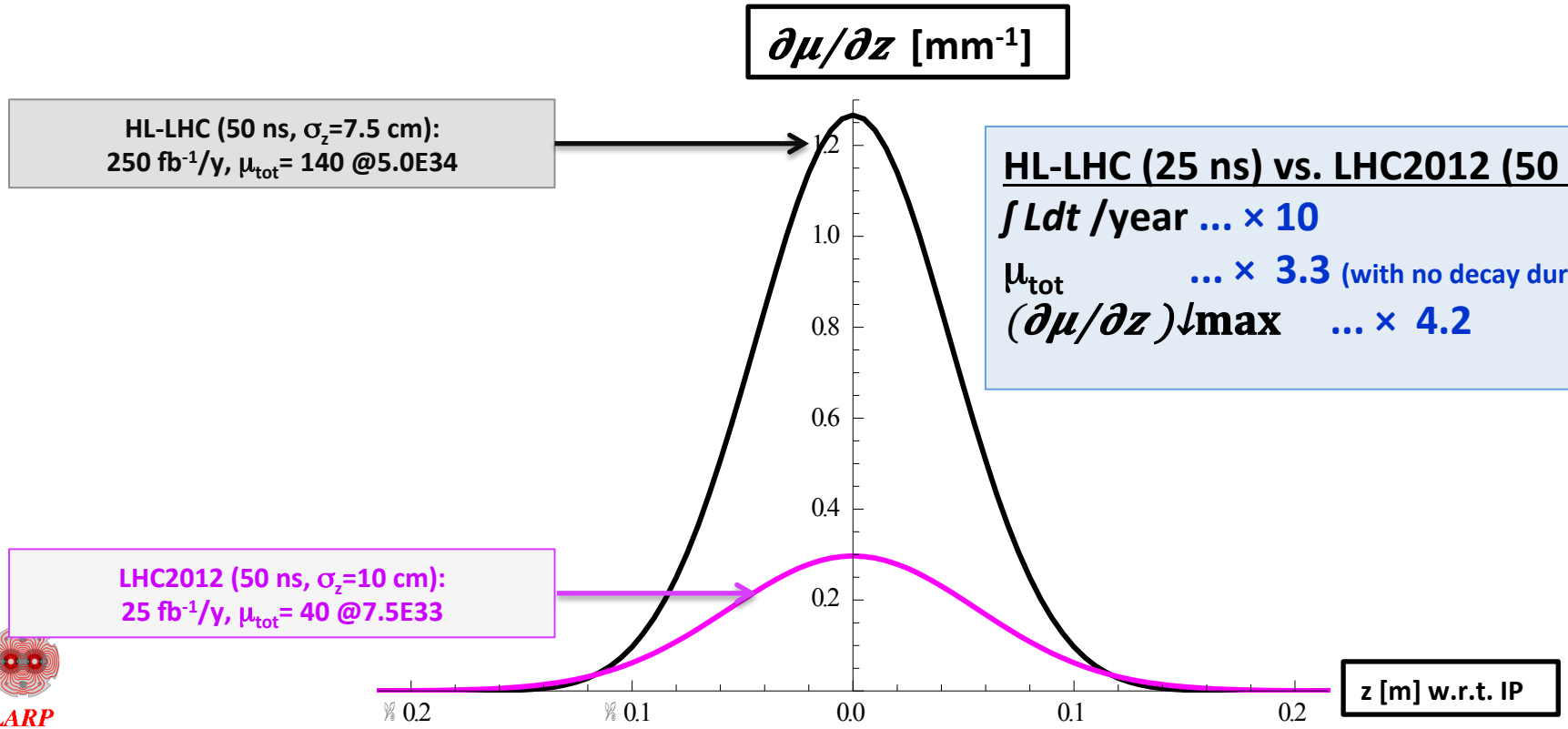
- **Vertex (Pile-up) line density (2d big challenge)**

→ **1.3 (1.8) evt/mm peak line PU density** @ μ_{tot}=140 (with tails @ 200) and 15 cm β^*

... The experiments are investigating (see B. Di Girolamo @ 2d HiLumi meeting, Nov. 2013)



HL-LHC (25 ns) vs. LHC2012 (50 ns):

$\int Ldt$ /year ... × 10

μ_{tot} ... × 3.3 (with no decay during fill)

$(\partial\mu/\partial z)\downarrow$max ... × 4.2

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Approach to beam-beam modeling

- Evaluate the robustness of various collision schemes using weak-strong simulation
  - Well-developed, reliable, and relatively fast approach
  - However
    - No coherent effects – need strong-strong
- <u>First pass of evaluation, to be refined with more detail</u>

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Model

- **Lifetrac** particle tracking code (D.Shatilov, BINP)
  - Full detail of machine lattice, element-by-element thin lens
    - Crab cavities
    - 2nd harmonic RF
    - Automatic conversion from mad-x
  - Weak-strong beam-beam with all collisions.
    - Crabbing of strong bunch
    - Arbitrary longitudinal strong beam profile
    - Wire compensators
  - The code underwent significant development since Tevatron – synergistic with Fermilab's AARD needs

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Model

- Evaluated quantities:
  - Dynamical Aperture
  - Frequency Map Analysis for resonance identification
  - Multiparticle beam parameters (intensity, luminosity, emittance lifetimes)

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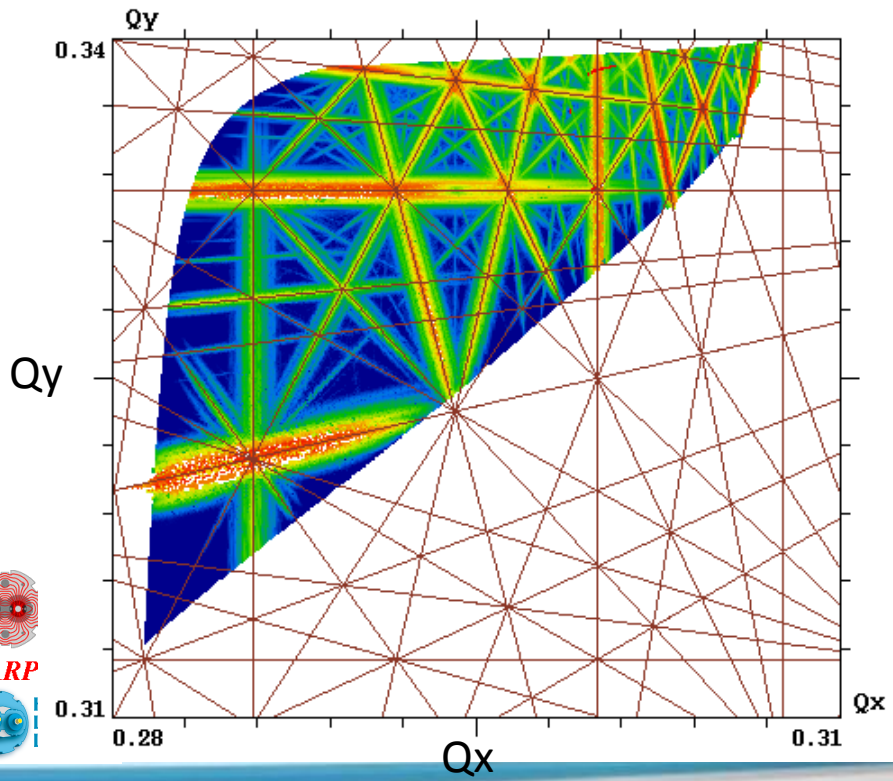
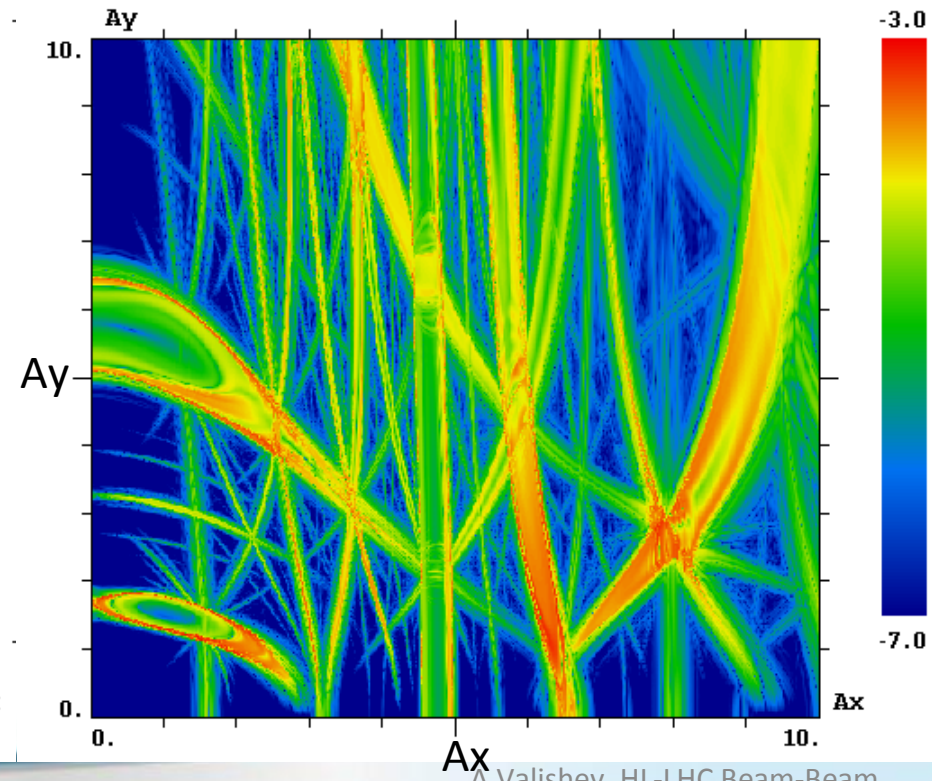
Frequency Map Analysis

- Based on precise tune determination from FFT of turn-by-turn particle coordinate. (J. Lascar, "The Chaotic Motion of the Solar System: A Numerical Estimate of the Size of the Chaotic Zones", Icarus 88, 266, 1990)
- Evaluate tune jitter in sliding time window ➔ resonances





Baseline HL-LHC scheme simulation

- Beginning of fill is 'trivial' despite large ξ – 3 head-on IPs, very weak long-range (>16 σ separation, compensated IR1-IR5)
- Middle of fill – significant head-on <u>and</u> long range
- End of fill – weak head-on
- <u>Question: how low can the CC voltage be?</u>

Leveling at L=5E34 (except * case)

β^* (cm)	Np (10^{11})	x-angle (μrad)	bb sep. (σ)	CC (MV)	ξx	ξy
69	2.2	360	16	7.7	0.0306	0.031
40	1.65	360	12	7.7	0.023	0.024
40	2.2*	360	12	7.7	0.0306	0.031
15	1.06	590	12.5	12.5	0.015	0.016
15	1.06	440	9	9	0.015	0.016

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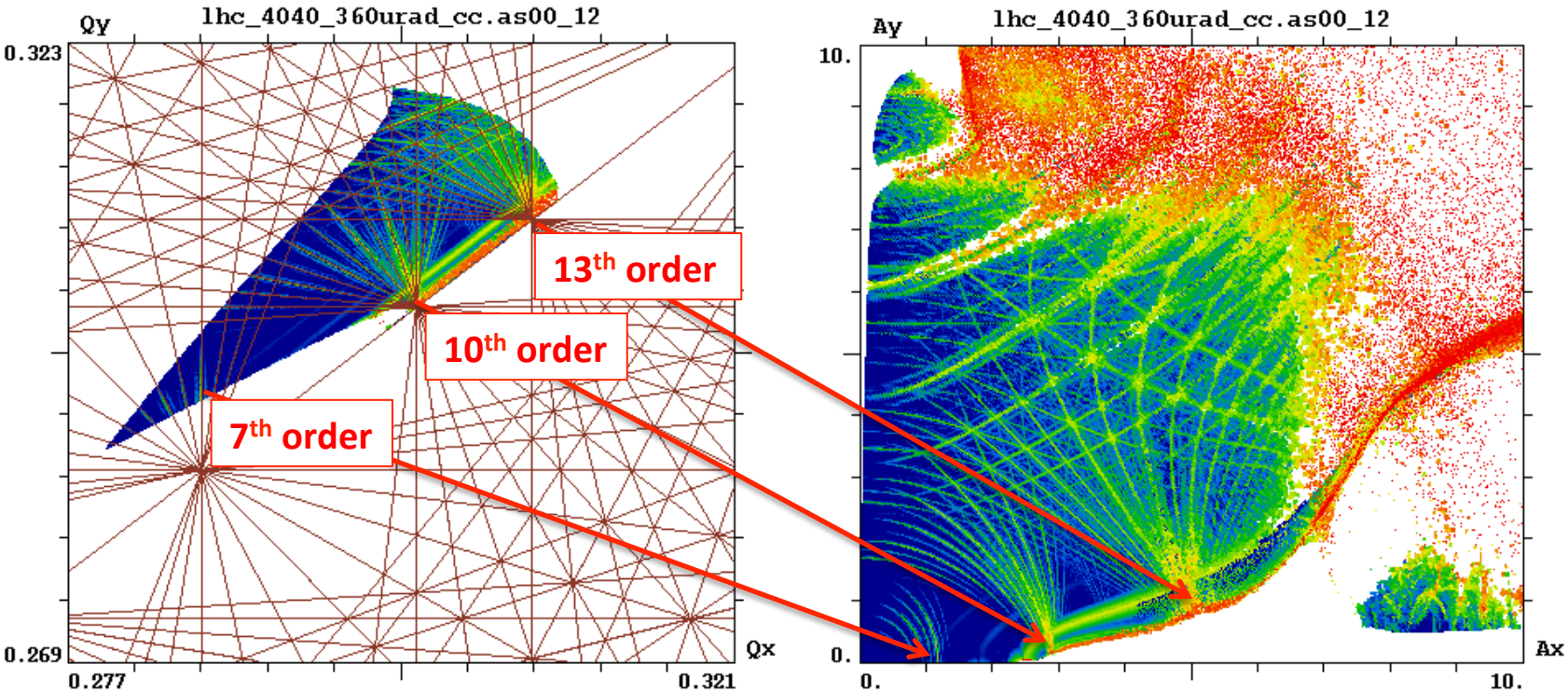
Baseline HL-LHC scheme results

beginning of fill

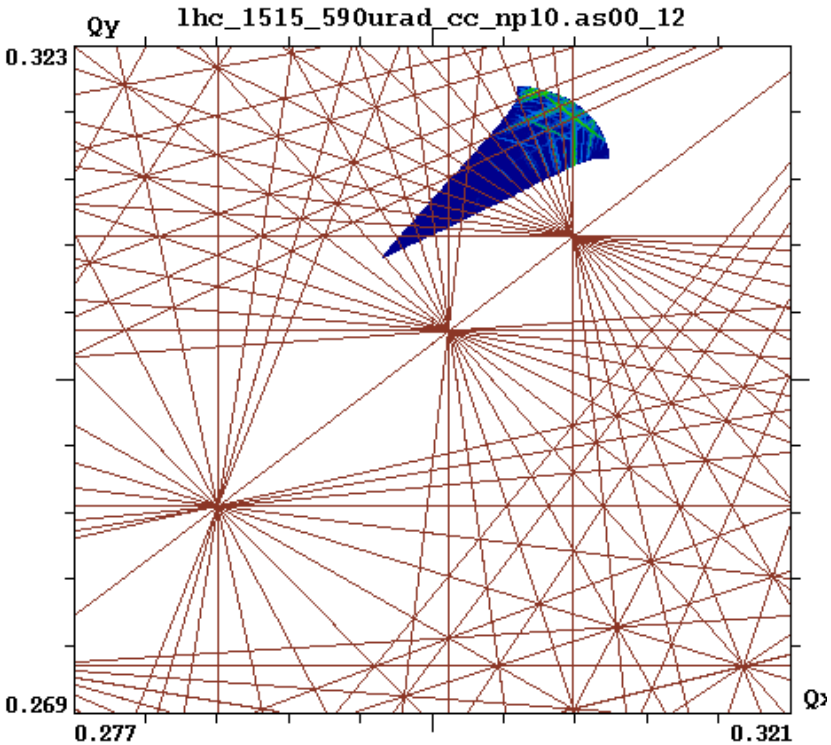
b=40 N_p=2.2* x=360 A=12 CC=7.7MV ξ_x=0.0306 ξ_y=0.031

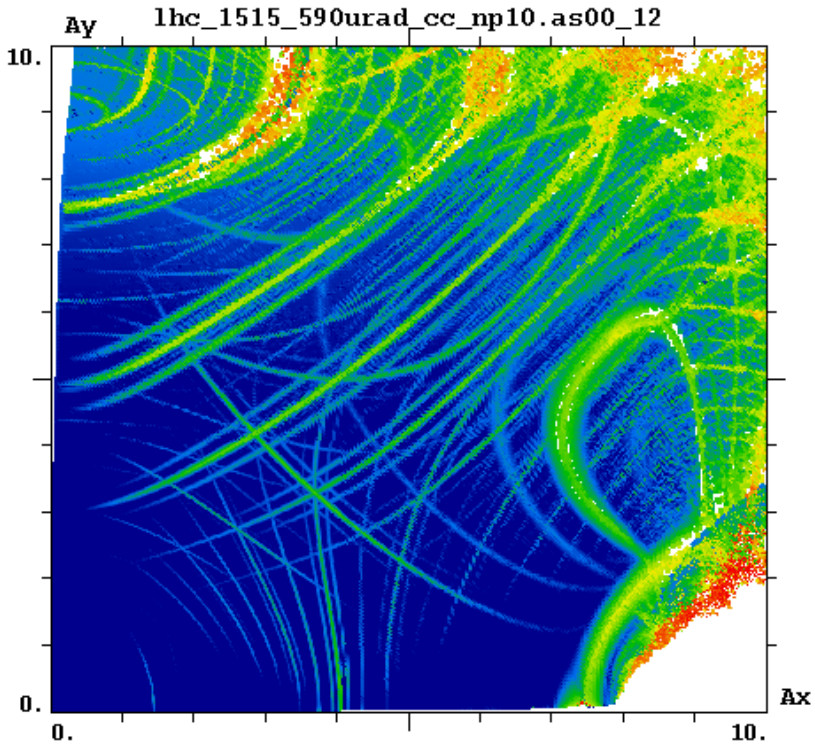


Baseline HL-LHC scheme results

end of fill

b=15 Np=1.0* x=590 A=12.5 CC=12.5MV ξx=0.015 ξy=0.016





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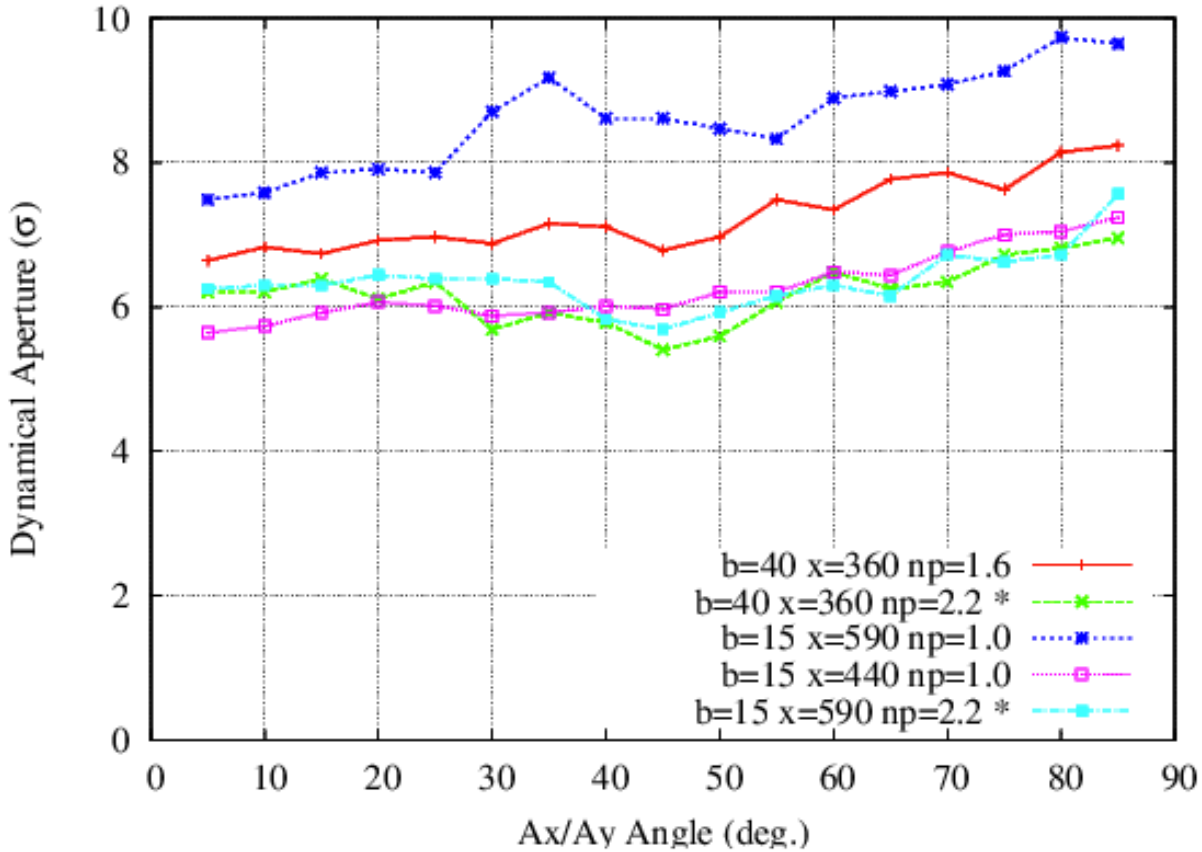
Baseline HL-LHC scheme results: DA



- <u>Conclusion:</u> baseline HL-LHC with CC is robust (nb: pileup density is a problem). <u>The CC voltage requirement may be re-visited</u> (However, the emittance growth must be accounted for and effect of imperfections must be studied)

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Need for a new scheme

... We need a ***leveling tool*** *which preserves the integrated performance but can* ***alleviate simultaneously***

1. The instantaneous luminosity (# PU / crossing)

2. The head-on beam-beam interaction

3. The peak line pile-up density (# PU/crossing/mm)

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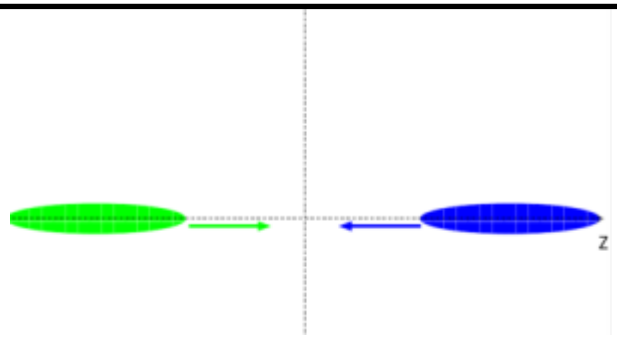
The 'Crab-Kissing' (CK) scheme

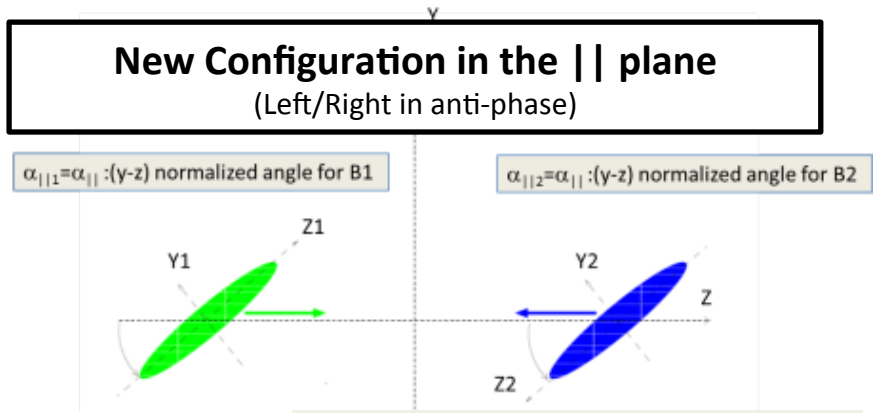
S.Fartoukh

- **What if one adds crab-cavities ALSO in the plane perpendicular to crossing ?**

Usual configuration in the || plane



New Configuration in the || plane
(Left/Right in anti-phase)



Typical "Side-Slip angle" of **100-150 μrad**

→ A tool for **levelling the collision time** is exactly what we need to correlate luminosity, PU line density and HO bb tune spread.

→ **Flat optics ($\beta x \neq \beta y$),** is a natural choice for minimizing the CC voltage required in both planes (i.e. not mandatory but "practical")

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Crab-Kissing scheme

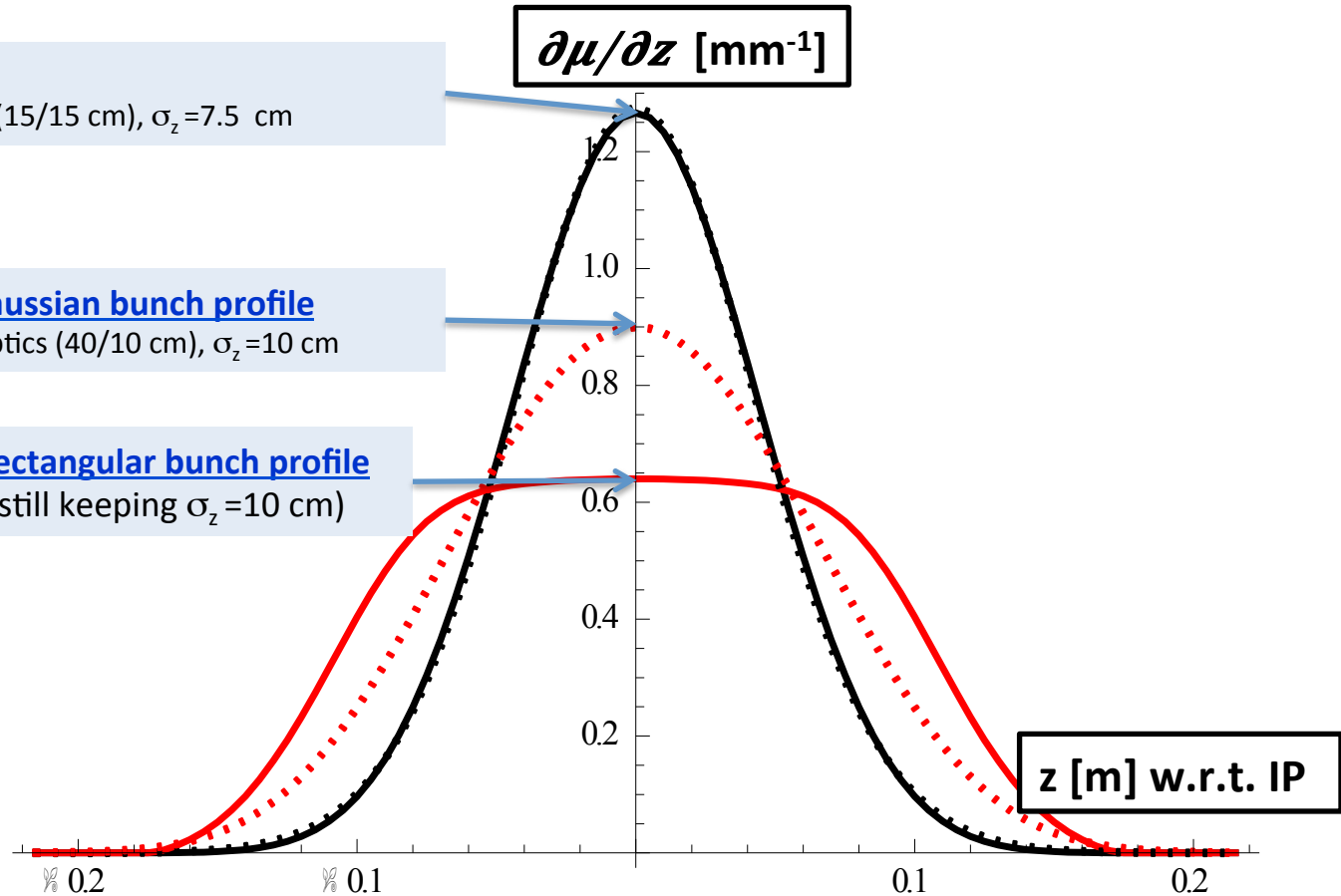
S.Fartoukh

- **The Pile-up line density and integrated performance**

HL-LHC w/o CK scheme
- **12.5 MV crabs in X-plane**, round optics (15/15 cm), σ_z =7.5 cm

"HL-LHC+" with CK scheme and **Gaussian bunch profile**
- **7+7 MV crabs in X and || -plane**, flat optics (40/10 cm), σ_z =10 cm

"HL-LHC++" with CK scheme and **rectangular bunch profile**
... with 400+800 MHz or 200+400 (still keeping σ_z =10 cm)



→ A net gain by a factor √2 at each step at nearly constant integrated performance

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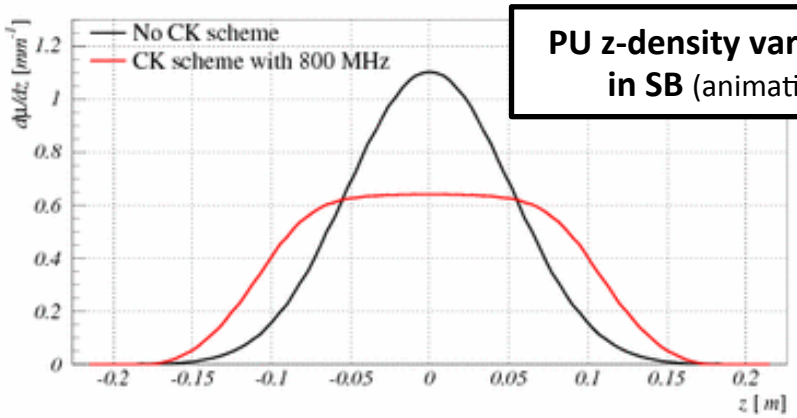
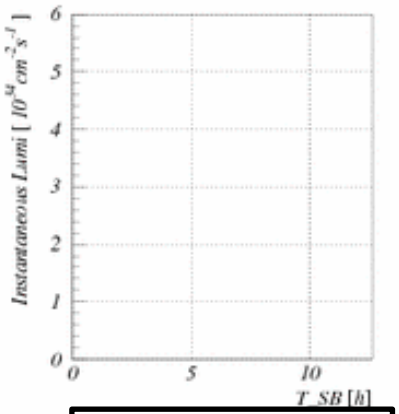
Crab-Kissing scheme performance

→ The **PU density shape** is changing in stable beam

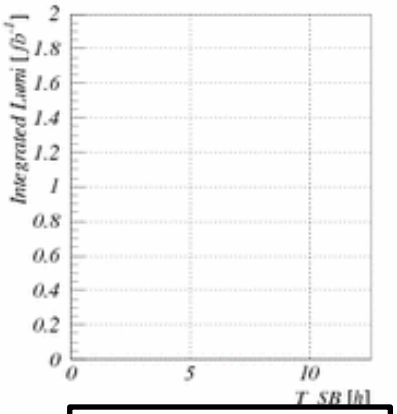
→ … but the **peak density** is halved and stays constant with the CK scheme at very similar integrated performance



PU z-density variations in SB (animation)



Lumi profile in SB



Perf. profile in SB

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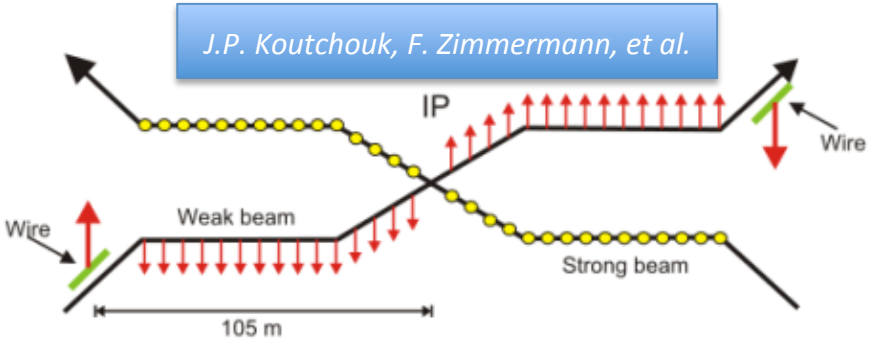
Long-range beam-beam wire compensators

- Implication of flat optics – no mutual compensation of long-range collisions at IP1,5 – large crossing angle to create 16-17 σ separation.

✓ Use current wires to allow reducing crossing angle

✓ Flat optics (β*= 50 / 10 cm) + wires represent HL-LHC Plan B w/o crab-cavity (5th HL-LHC coordination meeting, May 2013)



→ **Basic layout:** 2 wires/beam/side in between D1/2 (~380 A /wire for the HL-LHC beam)

→ **Main limitation: Machine Protection & collimation**

- The optimal correction is achieved when the wire normalized distance to the beam is slightly less than the beam-beam separation
- The wires cannot be closer to beam than the inner (less critical) collimator jaws

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Electron Lens as BBW

R. Steinhagen, 3rd Joint HiLumi LHC-LARP Annual Meeting, Daresbury 2013

- No limit on the distance from circulating beam
- Easy position adjustment, no mechanical moving parts

A.Valishev and G.Stancari, `http://arxiv.org/abs/1312.1660`

- In the simplest case wire must compensate the kick of N_{LR} collision points $\mathcal{L}_1 = eN_p c(1+\beta) \cong 2ecN_p = 2ec \times 2.2 \cdot 10^{11} = 21\ A \cdot m$
- Current wire produces kick through magnetic field

$$\Delta p_r = \int e\beta c B_\varphi dt = (L \cdot I) \times \frac{e}{2\pi\varepsilon_0 c^2}\frac{1}{r} \qquad \mathcal{L}_{LR} = N_{LR}\mathcal{L}_1 = 18 \times \mathcal{L}_1 = 378\ A \cdot m$$

- Electron Lens produces kick through electrical and magnetic field: gain factor 6 in current! $\Delta p_r = \int e(E_r + \beta c B_\varphi)dt = (L \cdot I)\frac{1 \pm \beta\beta_e}{\beta\beta_e} \times \frac{e}{2\pi\varepsilon_0 c^2}\frac{1}{r}$

L_{EL}=63 A m

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Ingredients of Crab-Kissing scheme

- Flat optics
- Wire beam-beam compensator (BBW)
- Crab-Crossing, Crab-Kissing
- Flat bunches

- <u>But can take advantage of individual ingredients even with incomplete set</u>

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Flat optics and BBW

- Flat optics 40/10 cm, σ_z=10cm
  - Small Piwinski angle to reduce luminosity loss
    - L/L_0=0.71 @ θ=340 μrad (11.7σ separation) σ_z=7.5cm – compare to 0.34 in nominal
    - L/L0=0.62 @ θ=340 μrad σ_z=10cm
  - Pileup density without CC depends on Piwinski angle
    - ϕ=1.1 (and less with β* leveling) vs. ϕ=3.1 in nominal
  - Non-compensated long-range in IR1-IR5
- Wire compensator to mitigate long-range?
- <u>Can we operate without Crab Cavities at all (forgetting the still high pileup density)?</u>

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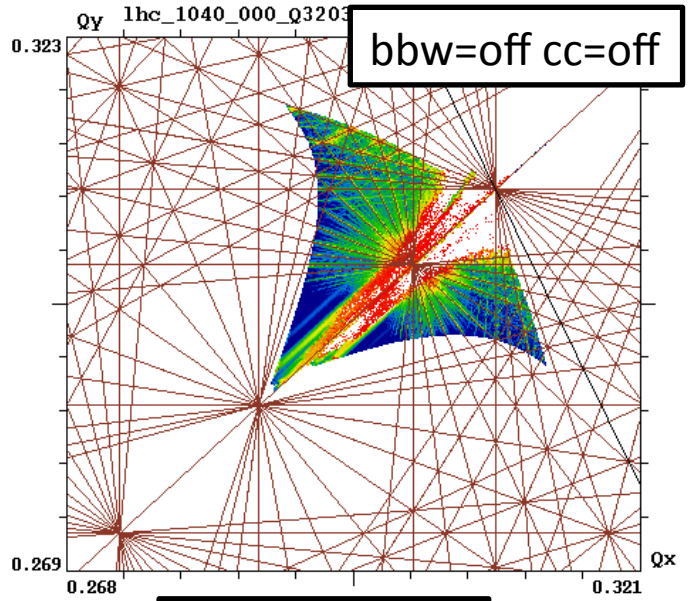
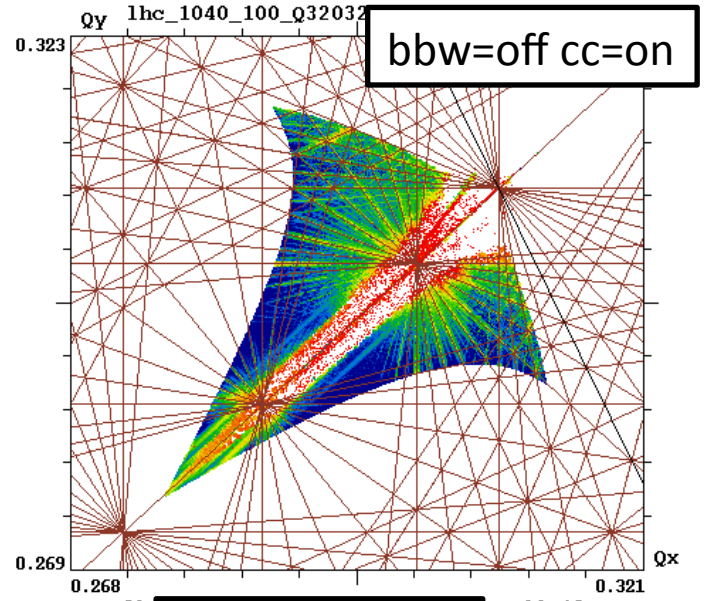
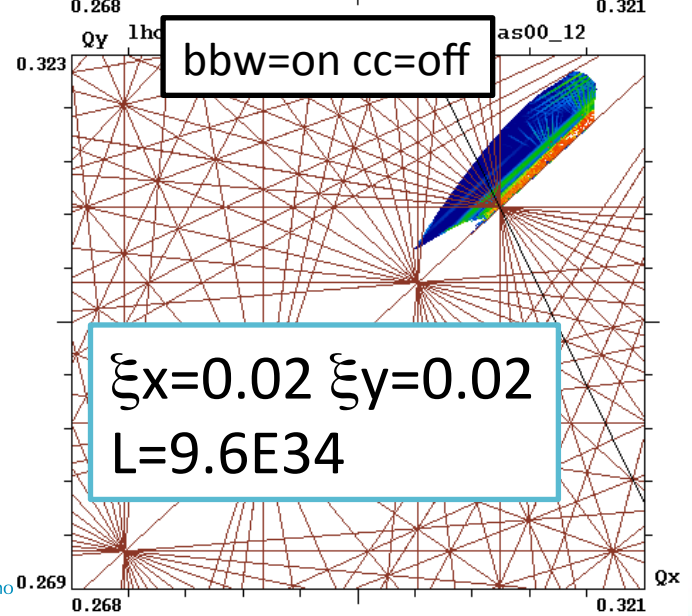
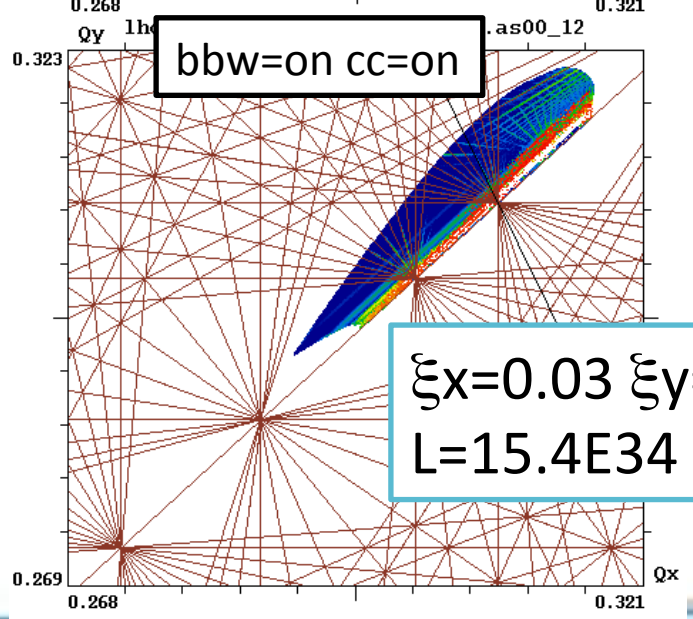
Flat optics and BBW results









x-angle 340 μrad, 11.7σ sep., σz=10cm, Np=2.2E11

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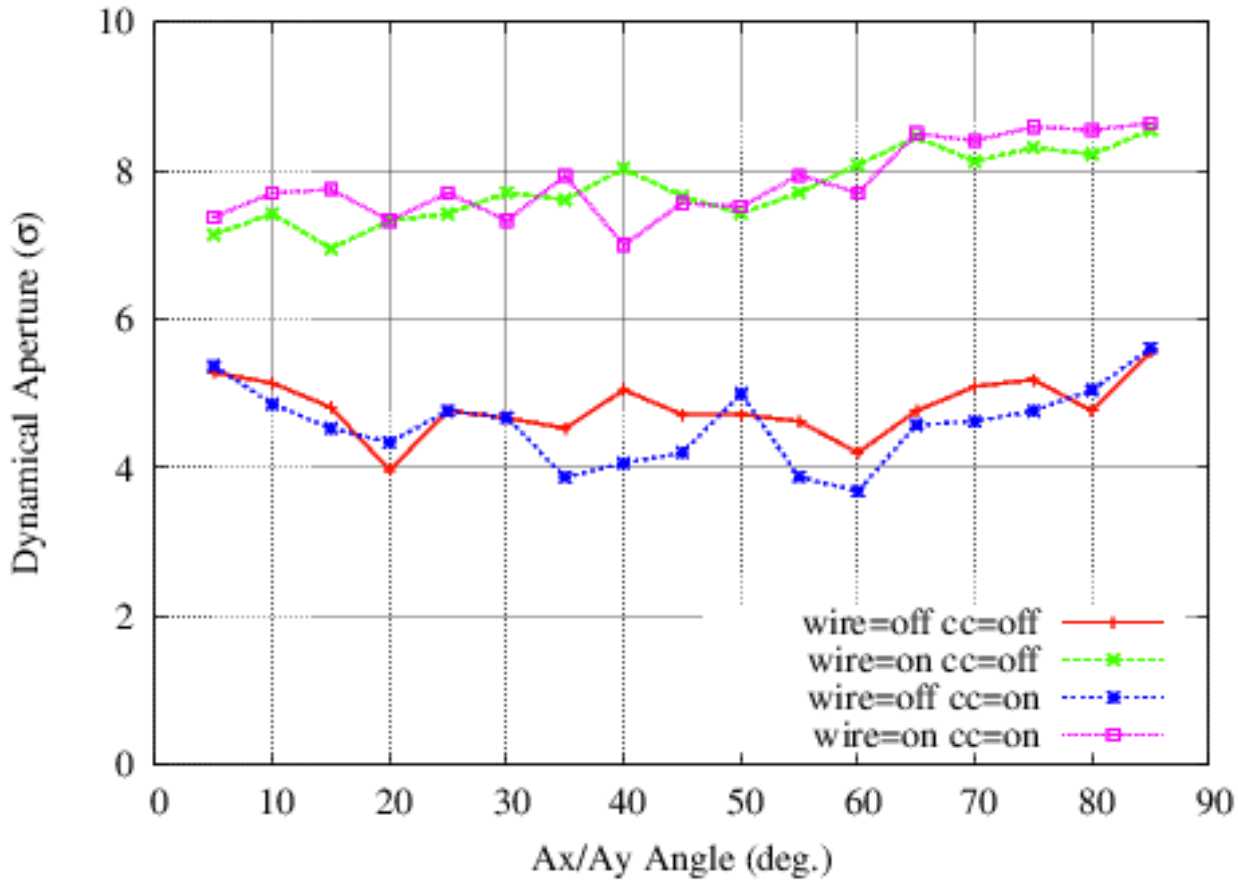
Flat optics and BBW results: DA



- Can operate without Crab Cavities but the pileup density is at the same level as in nominal scheme

Adding Crab-Kissing

- Flat optics 40/10 cm, 340 μrad
- Wire compensator
- Crab-Kissing (7MV in parallel separation plane – θ=165 μrad) – mitigate the pileup density
- Crab Crossing (up to 7MV in crossing plane) – recover luminosity loss due to CK

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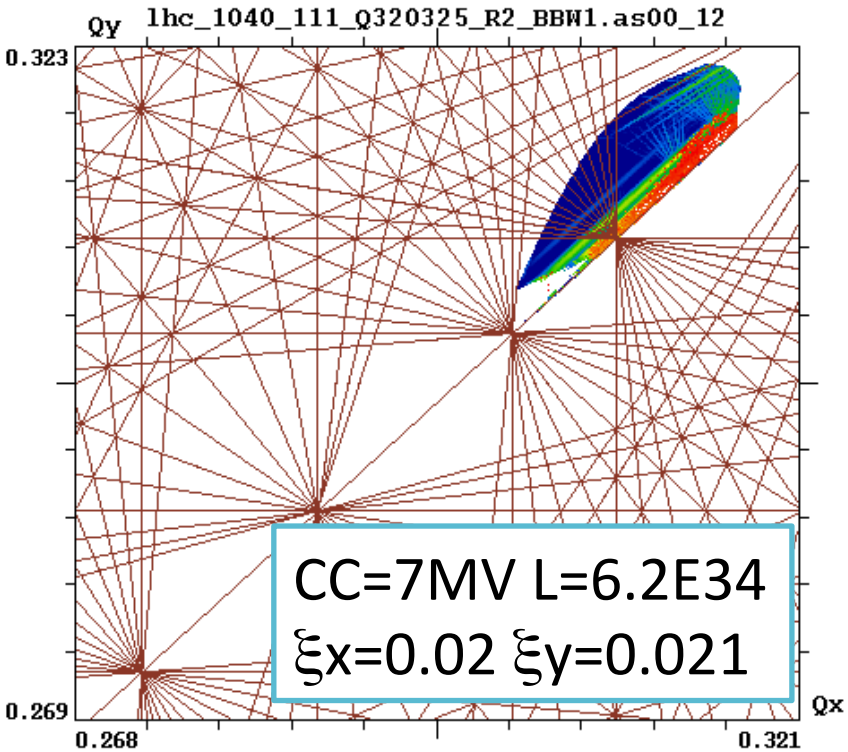
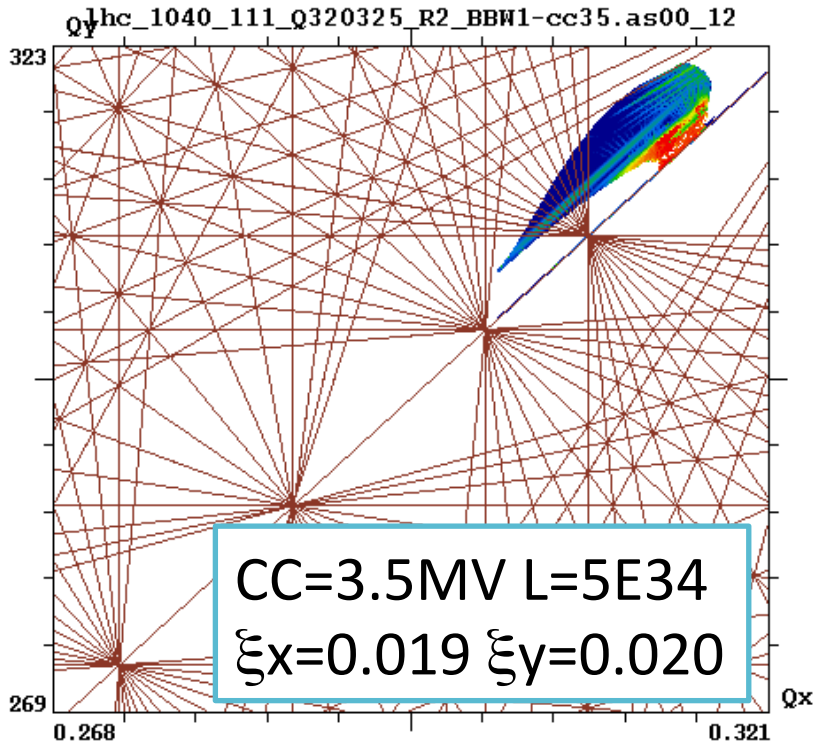
Crab-Kissing results

b=40/10 Np=2.2 x=340 A=11.7 CK=7MV, σz=10cm Gaussian



CC=7MV L=6.2E34
ξx=0.02 ξy=0.021



CC=3.5MV L=5E34
ξx=0.019 ξy=0.020

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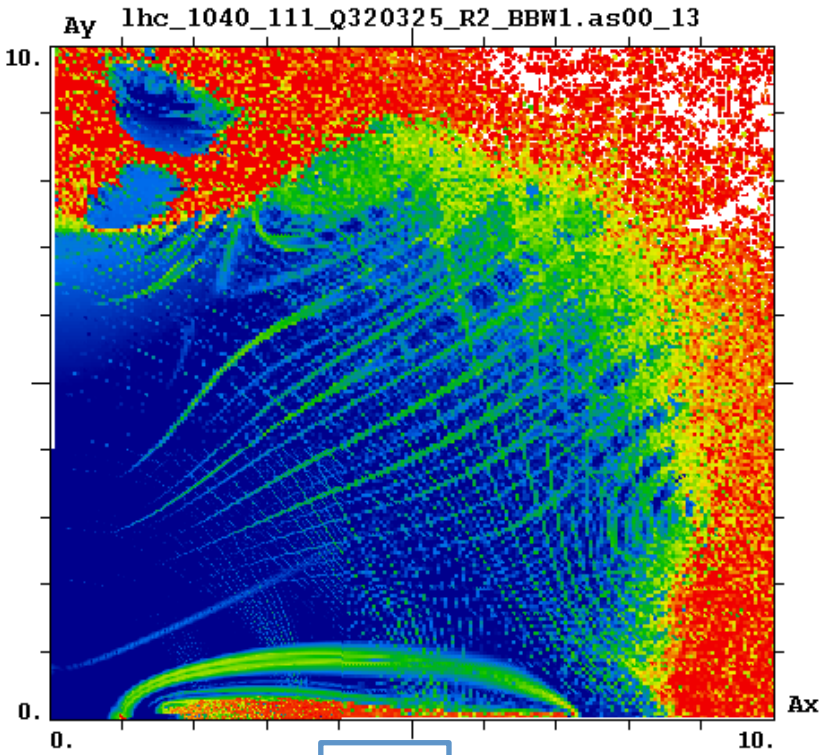
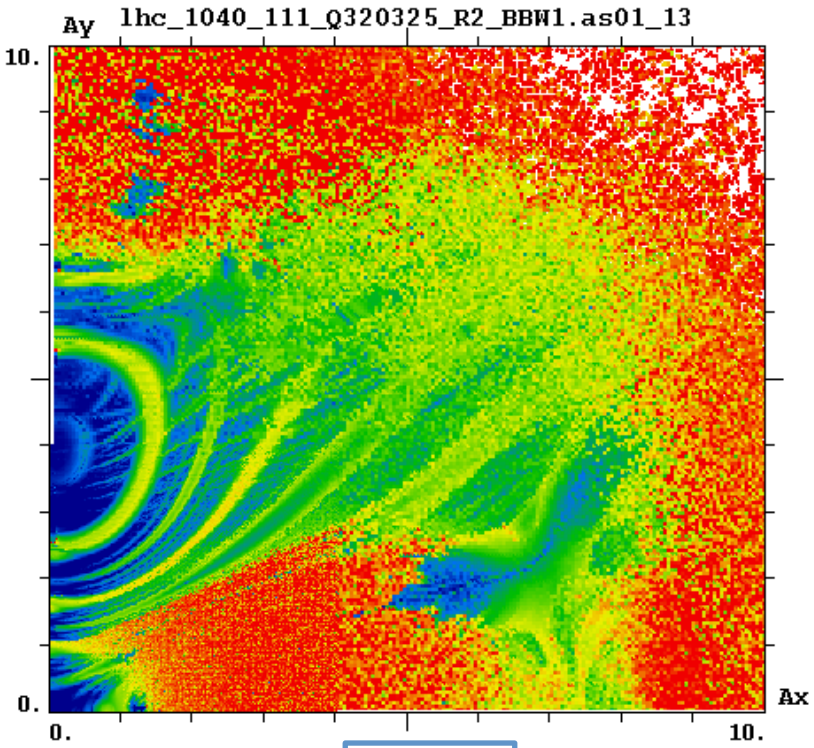
Crab-Kissing results:

synchro-betatron resonances

b=40/10 Np=2.2 x=340 A=11.7 CK=7MV CC=7MV



A_s=0



$A_s=1\sigma$

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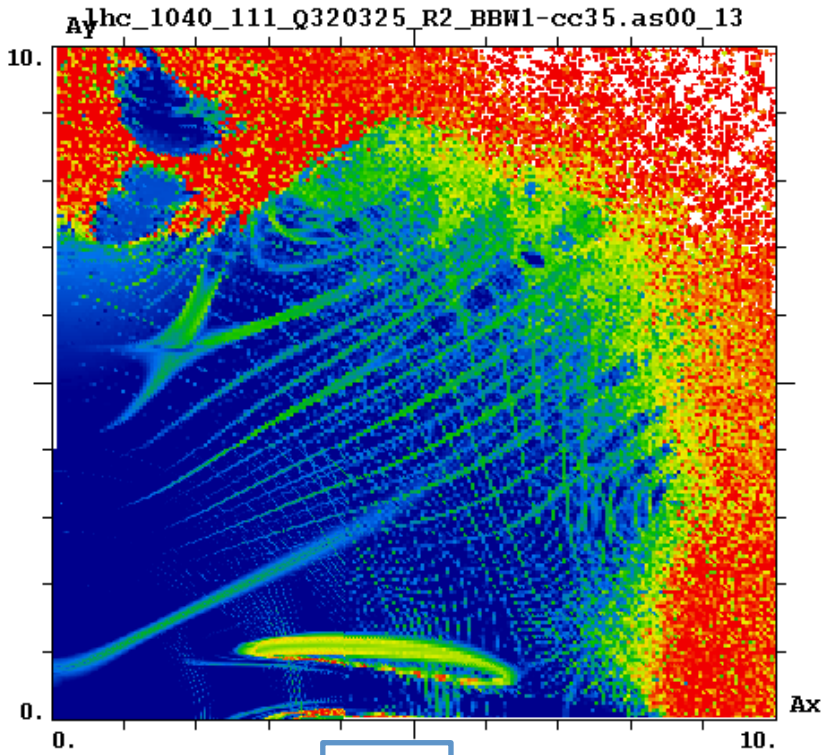
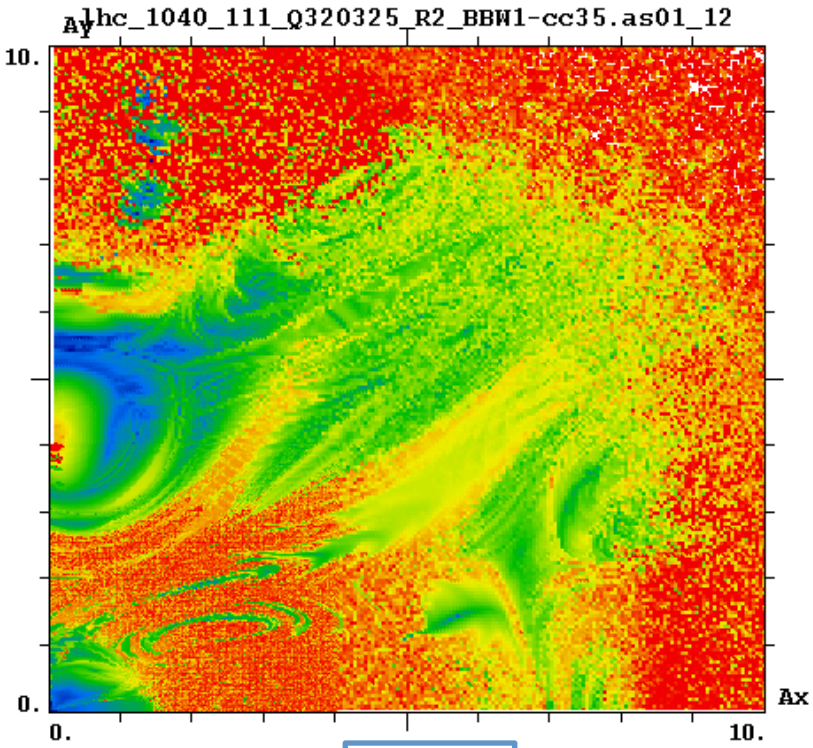
Crab-Kissing Results

synchro-betatron resonances

b=40/10 Np=2.2 x=340 A=11.7 CK=7MV CC=3.5MV

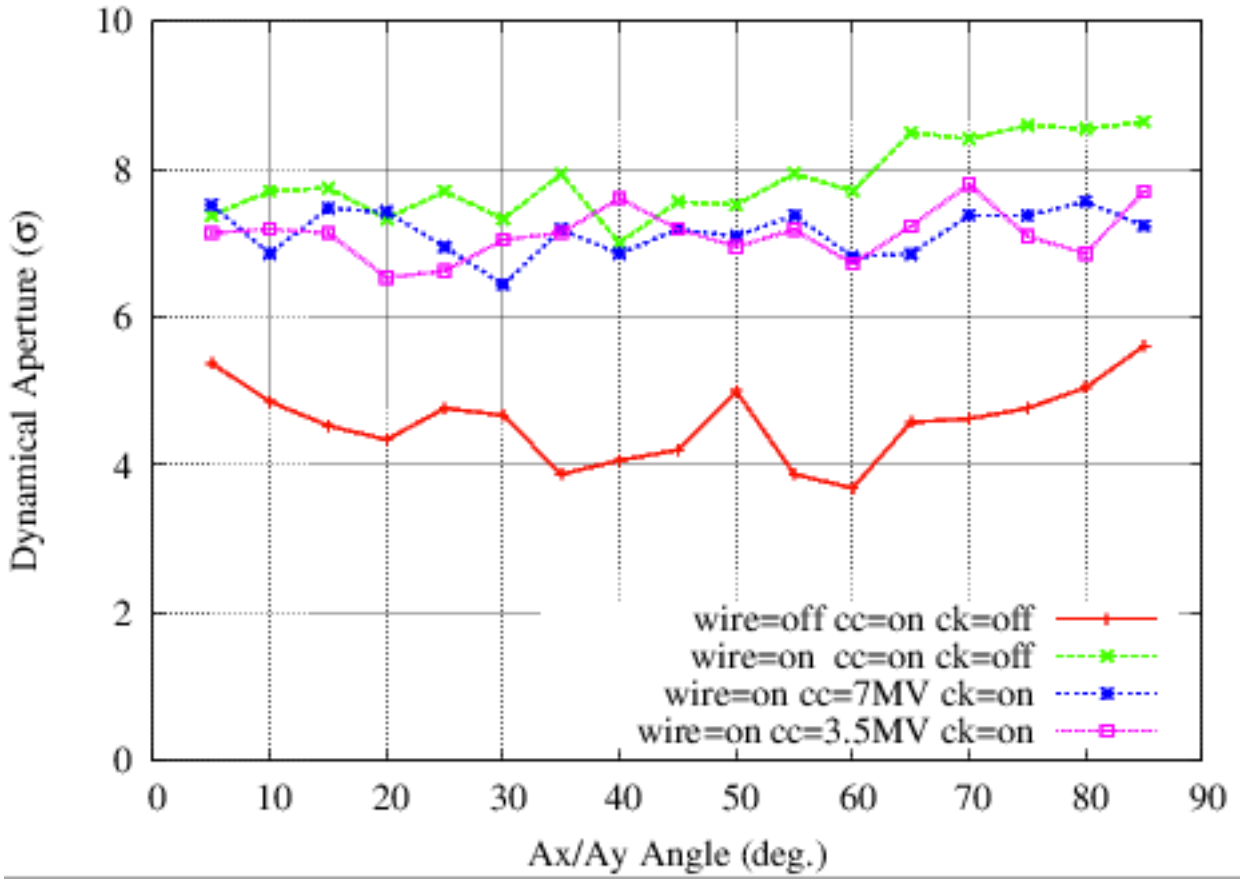


A_s=0



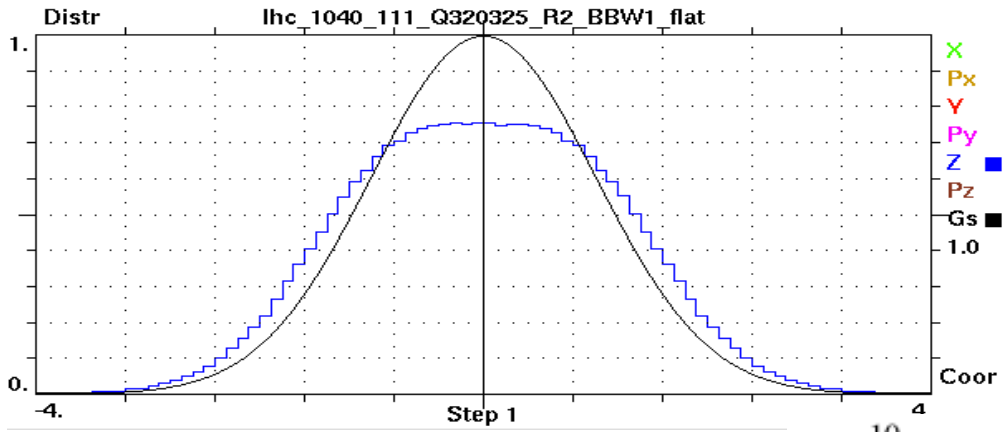
$A_s=1\sigma$

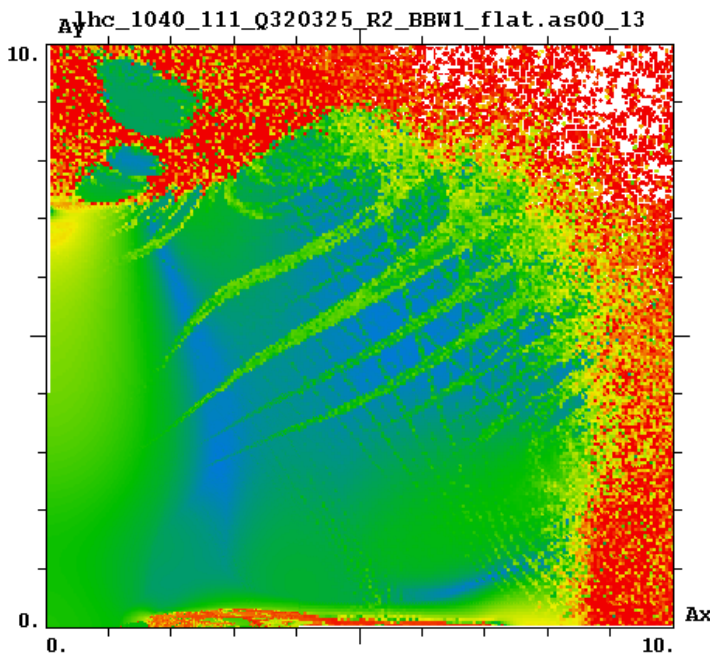
Crab-Kissing results: DA

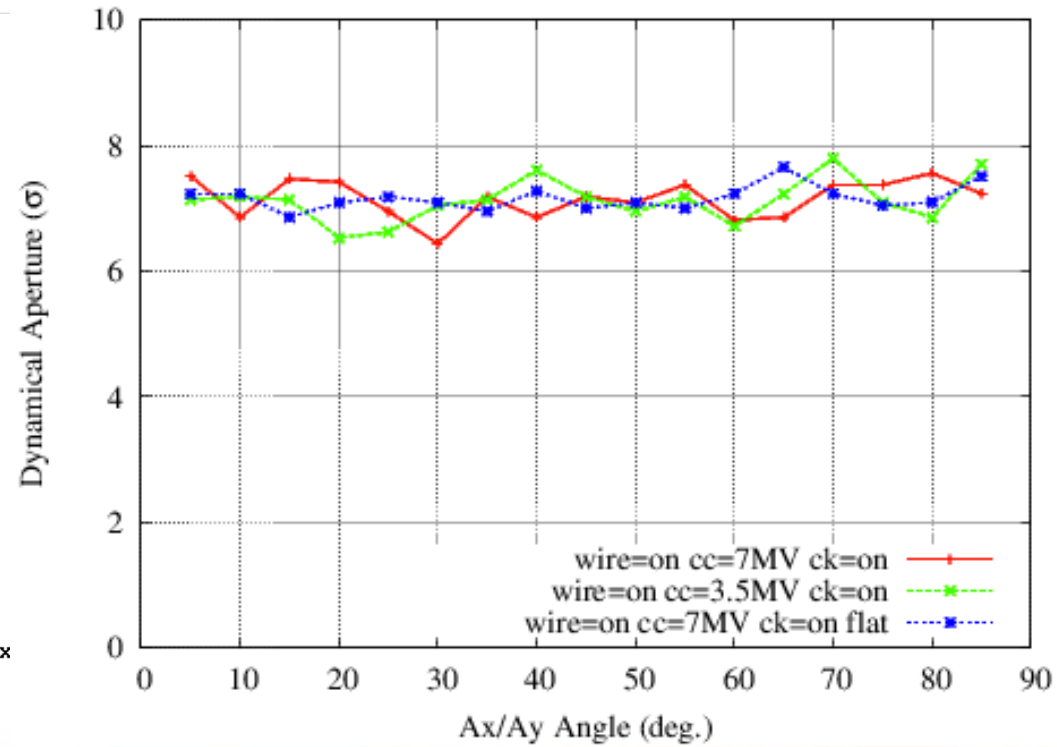


Not shown – multiparticle simulations of luminosity evolution

Altogether: Crab-Kissing, BBW, Flat Bunches







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Optimization of parameters – Omitted

- Distance to wire with 340 μrad in the presented optimized case is 10 σ beam (8.5 σ collimation)
  - Alternative solution exists to place wire at 11.5σ (10σ collimation)
- Resonance Driving Terms to cancel with wire
  - Position of the wire
  - Importance of IR8 – adds 0.01 tune shift and enhances 10×Q_x resonance
  - Optimization of tune working point

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Summary

- Beam-beam effects do not present a significant issue for the nominal LHC. However, the HL-LHC upgrade is challenging with respect to beam dynamics
- A HL-LHC performance scenario should be envisaged, that
  - Allows luminosity leveling
  - Keeps pile-up density as low as possible
  - Is robust with respect to beam-beam effects (no particle losses or emittance growth)
- Baseline HL-LHC scheme makes use of Crab Cavities and luminosity leveling with β^*
  - Weak-strong beam-beam is not a problem despite ξ=0.03
  - Pile-up density is high

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Summary

- A risk reduction solution without Crab Cavities based on flat optics and beam-beam wire compensation is feasible (HL-LHC 'Plan B')
  - Pile-up density is high
- Crab-Kissing scheme in combination with BBW and 2nd harmonic RF allows to halve the pileup density ➔ <u>may open way to increase of leveled luminosity beyond 5E34</u>
  - Backwards compatible with the baseline
  - Robust w.r.t. weak-strong beam-beam
  - Preliminary strong-strong results from K.Ohmi do not indicate any showstoppers for CK
  - Further optimization and investigation of imperfections is required

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